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THE JOURNAL OF
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STATISTICS AND ENGINEERING PRACTICE*

By B. P. DUDDING, M.B.E., Ph.D., and W. J. JENNETT, B.Sc.(Eng.), Associate Member.

[*Paper first received* 9*th June, and in revised form* 20*th November*, 1939; *read before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 19*th February*, 1940. *The paper would also have been read and discussed before* THE INSTITUTION *on the* 4*th January*, 1940, *but the meeting was cancelled owing to the war*.]

SUMMARY

This paper was originally written merely as an elementary introduction to a discussion on the application to industrial problems of modern statistical methods. In view, however, of the alteration in the arrangements for meetings minor changes have been made, but the paper should still be read as an introduction to a general discussion on the subject.

The authors have had in mind particularly the scrutiny of test data obtained in the course of the development of new manufacturing procedures and in the control of established ones.

Having first dealt with the fundamental conception of variability and the basic effect of chance on the magnitudes of test values, an approach is made to the more elementary methods, illustrated by examples in order of increasing complexity. At the end of the paper it is indicated that extensions to the Analysis of Variance involving correlation and regression are useful aids in testing and research. The authors emphasize that the efficient use of the statistical tool can come only by practice, and that in no sense can it be substituted for sound technical knowledge, with which in all problems it must be combined.

(1) INTRODUCTION

This paper is concerned with an elementary review of methods, based on statistical theorems, which can be used to help engineers handling data influenced by a multiplicity of causes to answer a question which arises continually in industrial practice. Concisely and in general terms it may be stated thus:—When knowledge becomes available by examination of samples drawn at random from a bulk, what conclusions can reasonably be drawn as to the character of the bulk?

Although statistics, in the sense of political survey, dates from the eighteenth century, the theory of statistics as a distinct branch of science did not begin to flourish until the last quarter of the nineteenth century. In England the work of Galton and Karl Pearson, followed by that of R. A. Fisher, laid the foundations of the application of theory to many fields of science. Research workers in biological sciences and in the agricultural industry were the first to turn these more recent advances to practical use.

Whilst individual workers, notable among whom was W. S. Gosset who wrote under the pseudonym of "Student," had used statistical methods in industry early in the present century, the first evidence of the systematic application of these principles to industrial problems was the publication of a series of papers by W. A. Shewhart and his colleagues in the *Bell Technical Journal* of 1922 and subsequent years.

In 1919, one of the present authors became interested in the appraisement of the quality of industrial products and in research and development work directed towards improvement of quality. The publication of the papers by Dr. Shewhart tended to confirm his growing conviction that statistical methods were necessary when studying data derived from factory tests, and also encouraged the regular application of statistical principles to this work. At this time there appeared to be no general use of these methods in English manufacturing industry if published work can be used as a criterion, although the introduction of tables of allowances on the life performance of electric lamps (1924) and the sampling clauses in coal specifications (1930, 1931) provide evidence of their use in industry. Greater interest was stimulated by a series of lectures given by Dr. Shewhart at University College, London, in 1932. Subsequently, the British Standards Institution formed a Committee charged with the following terms of reference:—

(i) To report on the application and use of statistical methods in standardization and specification of quality.

(ii) To draw up a short report which would serve to awaken interest in the application of statistical methods on the part of manufacturers and others concerned with problems of standardization and specification.

* Communication from the staff of the Research Laboratories of the General Electric Company, Ltd., Wembley, England.

(iii) To consider what encouragement is necessary for the development of research on improved statistical methods and their application to industry.

(iv) To consider what steps should be taken to provide for co-operation with bodies in the United States of America and elsewhere instituted for similar objects.

Out of this activity also grew the formation of the Industrial and Agricultural Research Section of the Royal Statistical Society. The meetings of this Section have provided opportunities for technicians employed in industry to meet statisticians and for statisticians to meet and discuss with technical people the difficulties which arise in trying to apply statistical methods to the examination of industrial data.

That The Institution has been interested in this development is indicated by the publication of papers in its *Journal*[1,2] and in the *Students' Quarterly Journal*.[3] The Kelvin Lecture of 1938,[4] although not primarily directed to the consideration of industrial problems, called attention to the essentially statistical nature of life and science.

At the present time there are surely few industrial products which are not expected to conform with some standard of quality. Apart from measures taken to ensure that finished products will conform with quality standards demanded by consumers, standards are often imposed at various stages in the production process in order to reduce waste of material and, therefore, the cost of the marketable articles.

The maintenance of standards of quality invariably depends on engineers-in-charge taking action to diagnose and eliminate causes of changes in quality, the existence of which is suggested by the scrutiny of data derived from inspection and testing. On the one hand failure to recognize early any signs of a change in quality may have serious consequences and, on the other hand, much effort may be wasted if the suspicion that a change in quality has occurred is unfounded. Careful consideration will convince those experienced in the supervision of manufacturing processes that, apart from wasted effort, the staff of a factory will tend to develop a very undesirable mental outlook if repeated efforts are made to trace causes of trouble which do not exist.

A defeatist attitude may be adopted or changes in procedure may be made on inadequate grounds in order to provide some satisfaction for the efforts expended. Any such reactions will greatly add to the undoubtedly difficult task of maintaining a factory at a high pitch of efficiency with regard to the cost and quality of its products.

The main objects of the present paper are:—

To emphasize the essentially statistical nature of many technical problems, and the part that chance plays in many technical decisions.

To demonstrate the need for a technique which will give assistance in making deductions from test data.

To illustrate and briefly describe some of the more elementary methods, based on the theory of probability, which have been employed in industry.

To present them in an order which the authors' experience suggests will provide an easy mode of approach for an engineer employed in industry.

It is advisable to state in general terms how technical improvements and economies accrue to those industrialists who cultivate the statistical outlook, and who apply statistical methods to the scrutiny of technical data.

(i) Errors in judgment, arising from ambiguities due to the effect of chance, which lead to incorrect action, are reduced.

(ii) Development work involving reasonably large-scale production can be planned most economically and the results rightly appraised.

(iii) The efficiencies of specifications both for the internal control of factory materials and processes, and for normal commercial use, are improved when their compilation is guided by due appreciation of the errors which arise from chance causes.

(iv) Efficient and simple systematic methods of presenting data requiring daily scrutiny can be readily devised.

(2) FREQUENCY DISTRIBUTION OF OBSERVATIONS

When a large number of measurements are made on some dimension or quality of manufactured articles,

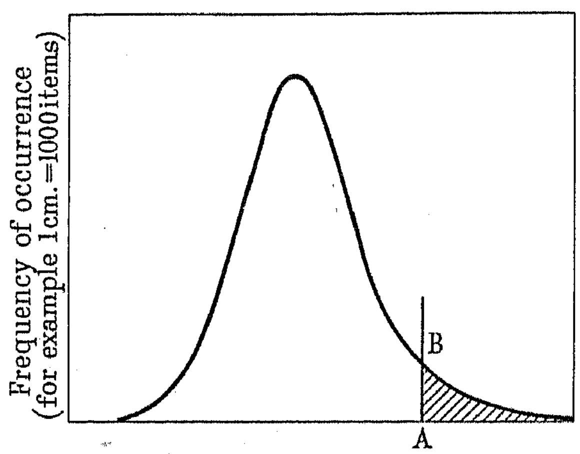

Fig. 1.—Frequency distribution.

it will generally be found that the observed values tend to be grouped in a characteristic manner. The frequency with which a value occurs diminishes as the difference of this value from a central value increases. The general arrangement of frequencies with which different values occur is known as the "frequency distribution" and may be illustrated by means of a frequency diagram of the type shown in Fig. 1. If a conception can be formed of the frequency distribution of the observed values which could be obtained by the examination of a large number of articles, then some estimate can be made of the likelihood of obtaining any specific value if an article is chosen at random from the bulk. Thus, in the diagram, the probability* of a random observation having a value greater than that corresponding to A is the area under the curve to the right of AB expressed as a fraction or a percentage of the total area under the curve.

Published theoretical work has been largely associated with the properties of the Normal or Gaussian distribu-

* It is advisable to point out that the authors use the word "probability" here and throughout the paper in the sense of "likelihood based on proportional frequency of occurrence."

tion, the formation of which was illustrated by Professor Born in the Kelvin Lecture of 1938.[4]

The Gaussian distribution has the property of being defined by the value of the mean and another quantity which is called the "standard deviation." The standard deviation is a measure of variation and is the root-mean-square of all the deviations of the individual values from the mean value. It is, therefore, analogous to the r.m.s. value of an alternating current flowing in a circuit. When a mean value and a standard deviation are associated with a large amount of data, they are usually represented by the symbols $\overline{X}$ and σ, but when associated with samples by $\bar{x}$ and s, respectively. The standard deviation is sometimes expressed as a proportion or percentage of the mean. It is then known as the "coefficient of variation."

For the Gaussian distribution, tables have been calculated and published[5] giving the area of the curve lying outside various deviations from the mean expressed as multiples of the standard deviation. It is convenient to

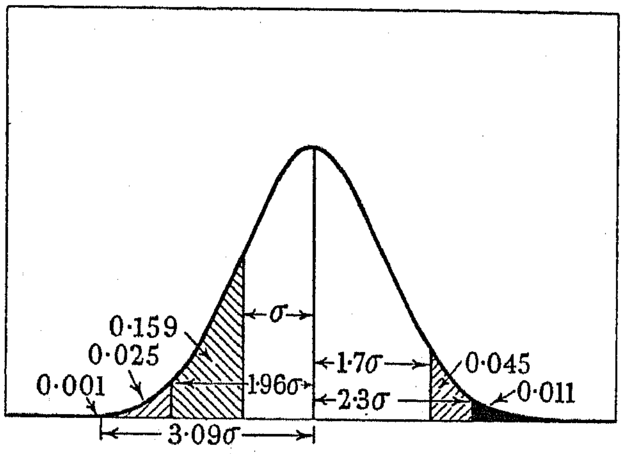

Fig. 2.—Gaussian distribution.

refer to deviations so expressed as "standardized" deviations. By using these tables, if the mean value and standard deviation of a Gaussian distribution are known, or can be inferred, the expected proportion of individuals within any desired range of the scale of measurement can be estimated.

For example, the proportion of observations having a value

less than $\overline{X} - \sigma$	or greater than $\overline{X} + \sigma$	is $0 \cdot 159$
less than $\overline{X} - 1 \cdot 7\sigma$	or greater than $\overline{X} + 1 \cdot 7\sigma$	is $0 \cdot 045$
less than $\overline{X} - 1 \cdot 96\sigma$	or greater than $\overline{X} + 1 \cdot 96\sigma$	is $0 \cdot 025$
less than $\overline{X} - 2 \cdot 3\sigma$	or greater than $\overline{X} + 2 \cdot 3\sigma$	is $0 \cdot 011$
less than $\overline{X} - 3 \cdot 09\sigma$	or greater than $\overline{X} + 3 \cdot 09\sigma$	is $0 \cdot 001$

These proportions are illustrated in Fig. 2.

Should the frequency distribution not be Gaussian it should be noted that the standard deviation is still a measure of the spread or variability of the data, but the proportions associated with particular standardized deviations would differ from those given above.

The engineer contemplating the use of established theoretical relationships is confronted with two principal dangers. On the one hand he may apply these theoretical relationships without any appreciation of the limitations which may be imposed because the distribution with which he is concerned departs from the Normal or Gaussian. On the other hand, in the absence of knowledge of the distribution, he may hesitate to use statistical principles at all.

However, experience shows that, where reasonable care is taken to control the processes of manufacture and measurement, there is a marked tendency for the distribution of observations to approach the Gaussian form. Many examples of such distributions are available, and a few are illustrated in Figs. 3–15.

In those cases where the distribution is not Gaussian, despite the fact that there is reasonable control of manufacturing processes, the general "single-hump" shape of the distribution is retained, but there is lack of symmetry (e.g. Fig. 7). However, it can be shown that if the average value derived from tests of samples as small as, say, 5 articles, be utilized, the distribution of these average values will show an increased tendency to be Gaussian whatever the nature of the distribution of the individual values. Hence it is clear that some of the theoretical relationships derived from the properties of the Normal or Gaussian distribution can be safely used in approaching practical problems if, in the early stages, attention is concentrated on the average results derived from small samples rather than on the individual values. As experience is gained, the limitations imposed by any assumptions made when interpreting data derived from samples become more readily appreciated and methods available for dealing with individual observations can be utilized without serious risk of error.

(3) CONTROL CHARTS

(a) Chart for Mean Values

There is no doubt that Shewhart's conception of a control chart, on which routine test data are plotted against limits, forms the best introduction to the application of statistical principles to industrial problems. In its simplest form it assumes that some measured quality of a manufactured article is represented by a frequency distribution similar to that already referred to, and that this distribution is fixed when the industrial processes proceed under normal conditions of control. As already explained the spread in such a distribution can be measured by the standard deviation and, if the limits Shewhart chooses (three times the standard deviation) be placed on either side of the central value it is clear from many of the illustrations already given that observations outside these limits should occur on very rare occasions. With this background the occurrence of an observation outside these limits is an indication to the engineer that something may be happening which suggests a lack of control of the materials or processes.

The association of a value of probability with limiting values displaced from the average value by a multiple of the standard deviation depends on the distribution of values approaching some established form, for example the Gaussian as illustrated in column 1 and in Fig. 2. Bearing in mind what has been stated at the end of the previous Section regarding approach to the Gaussian form, it is advisable, when making contact with statistical technique for the first time, to deal with the variation among average results for samples of, say, 5 to 10 individuals.

Even when samples are selected from the same bulk the average results for the different samples will inevitably differ because of the existence of variation in values for

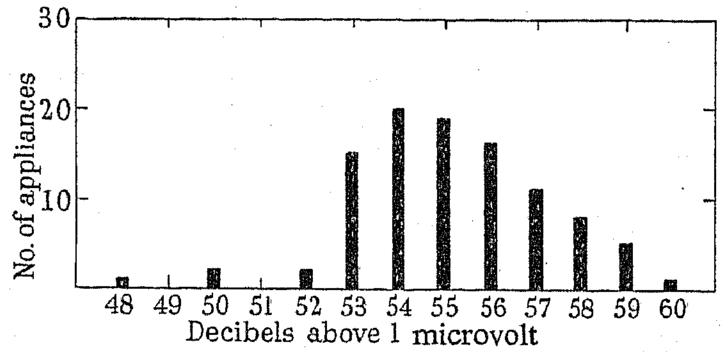

Fig. 3.—Radio interference from small domestic appliances.

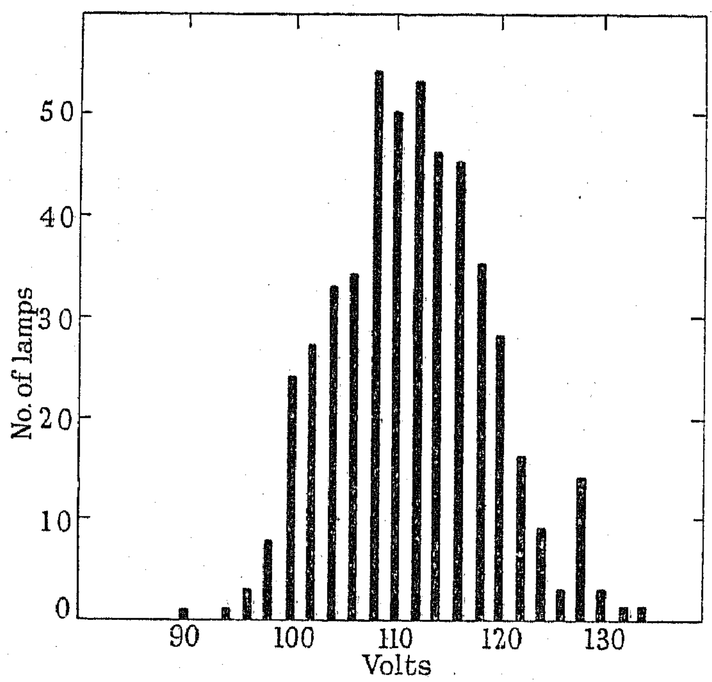

Fig. 4.—An electrical characteristic of 400-watt mercury-vapour discharge lamps.

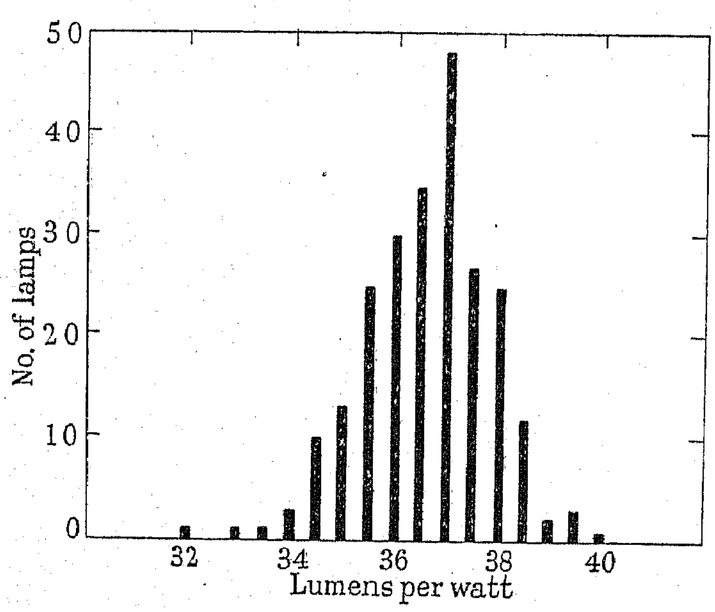

Fig. 5.—Initial efficiency of 250-watt mercury-vapour electric discharge lamps.

individual specimens. Hence, when studying the variation among the average results of samples, with a view to deciding whether they could have come from bulks having similar average qualities, allowance must be made for the variation which would exist even if the samples were drawn from the same bulk.

Irrespective of the form in which the individuals are distributed, the standard deviation of the mean values of samples containing n individuals is given by $\sigma/\sqrt{n}$, σ

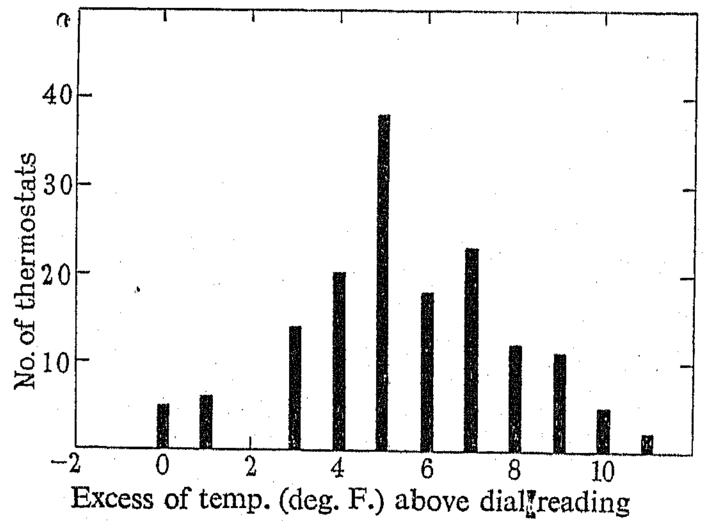

Fig. 6.—Errors in adjustment of thermostats used to control electrical heating apparatus.

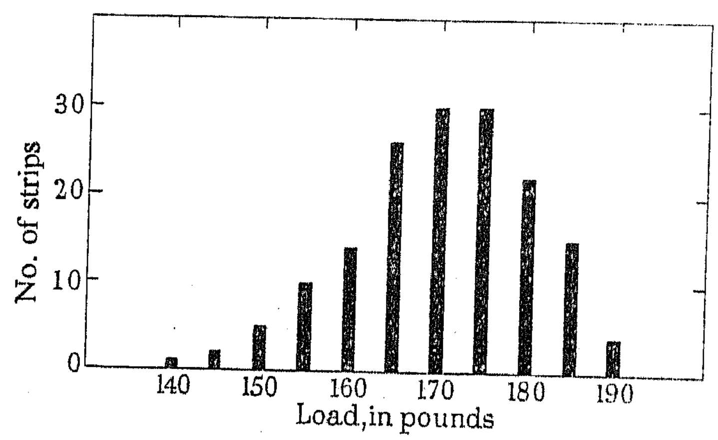

Fig. 7.—Breaking load of strips of cotton fabric.[6]

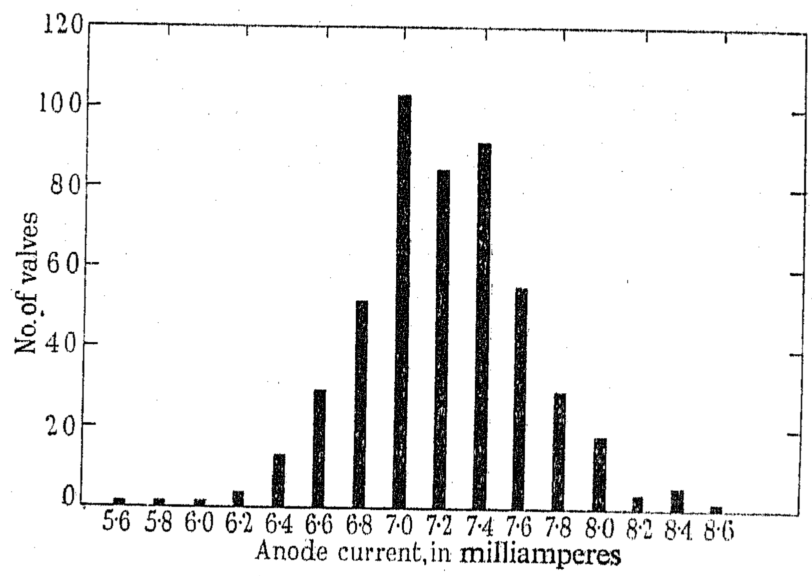

Fig. 8.—An electrical characteristic of receiving valves.

being the standard deviation of the individual results comprising the bulk from which the samples are selected. Thus, if the data under consideration are the average results derived from tests containing 4 or 9 individuals, the standard deviations of these average results will be respectively one-half or one-third of the standard devia-

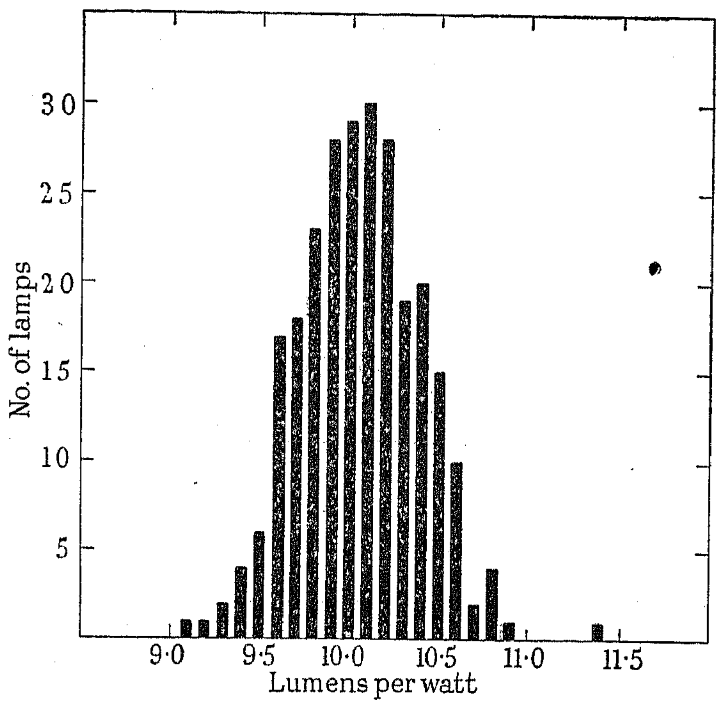

Fig. 9.—Initial efficiency of 40-watt electric incandescent lamps.

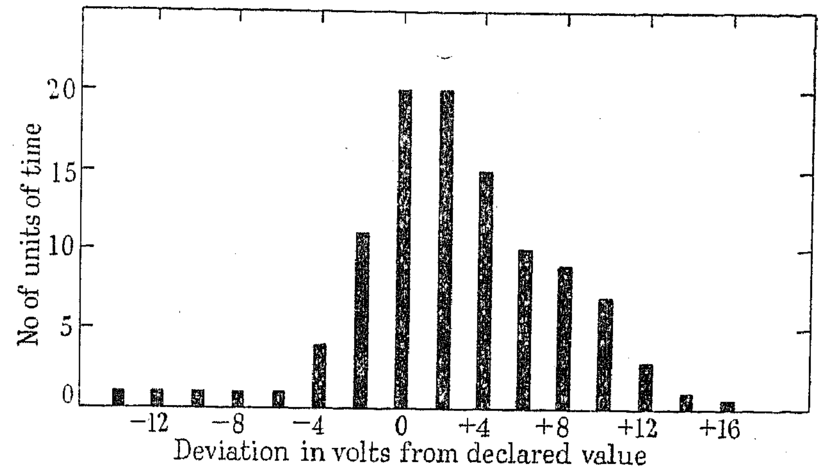

Fig. 12.—Voltage distribution on a network.[7]

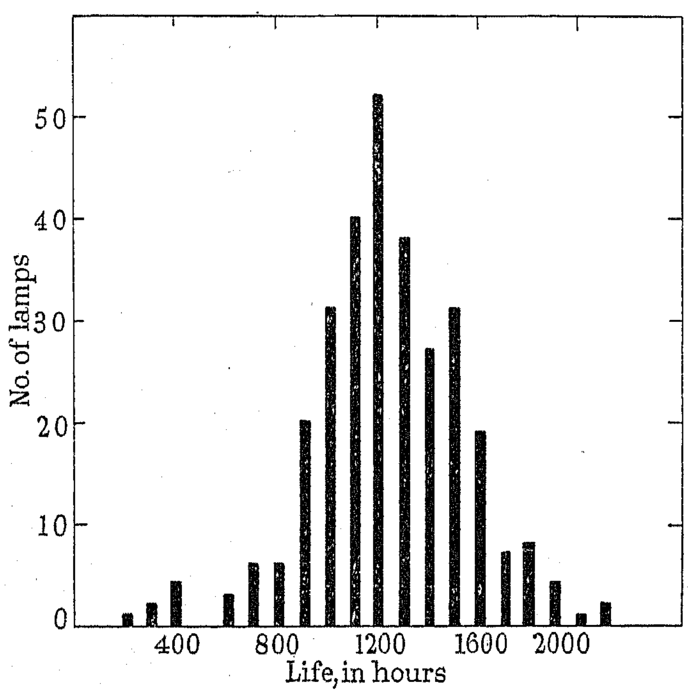

Fig. 10.—Lives of 100-watt electric incandescent lamps.

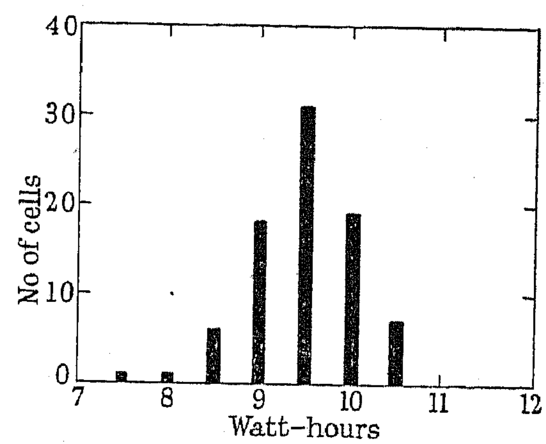

Fig. 13.—Watt-hour capacity of primary cells.

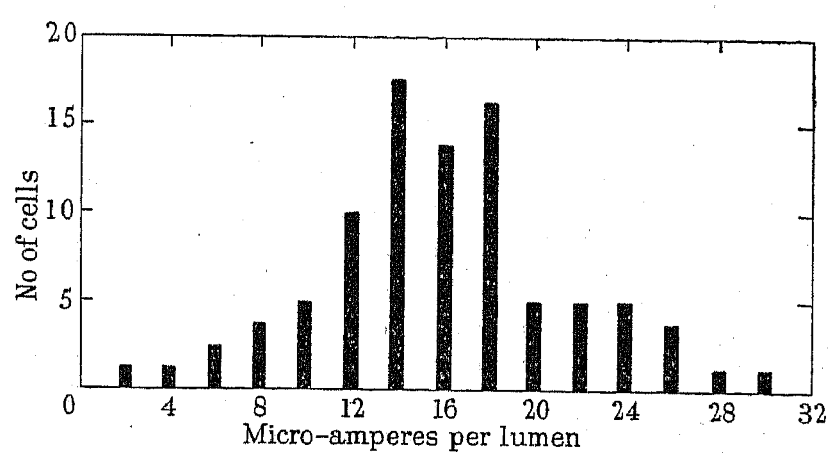

Fig. 14.—Sensitivity of photo-electric cells.

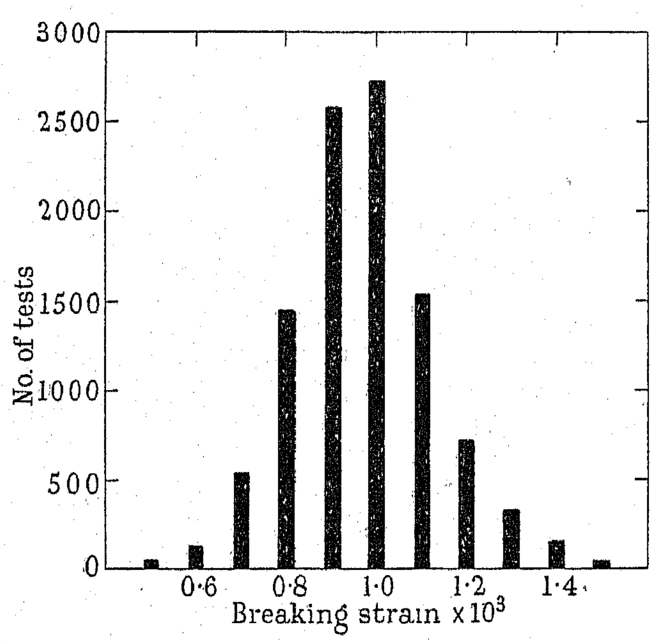

Fig. 11.—Breaking strain of glass tubing.

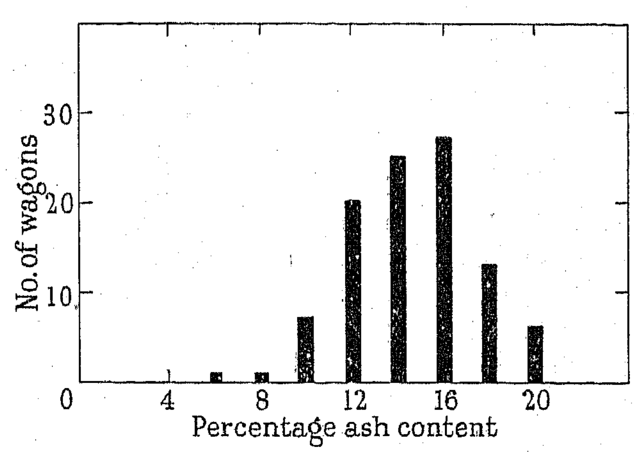

Fig. 15.—Percentage ash content in wagons of coal.[8]

tion of the individual results. Further, the average value of all the sample means will approximate to the average value of the individuals in the bulk. Hence, since an approach to the Gaussian form can be assumed, standard multipliers can be used to calculate limits within which the means of samples will be expected to fall on, say, 19 out of 20 or 499 out of 500 occasions, provided the bulk from which they are drawn has a specified mean value and standard deviation. For example, the means of samples of n individuals selected from a bulk with a mean value $\overline{X}$ and standard deviation σ will fall

19 out of 20 times between limits $\overline{X} \pm 1{\cdot}96\sigma/\sqrt{n}$
499 out of 500 times between limits $\overline{X} \pm 3{\cdot}09\sigma/\sqrt{n}$

The values of the mean results of samples relative to such limits will indicate whether it is likely that the samples have come from bulks whose quality values are consistent with those on which the limits are based. If data for samples selected from a regularly produced product are found to be consistent with the limits, the quality of the product can be said to be controlled. Such limits may therefore be known as "control limits" and the graphical representation as a "control chart." In effect a controlled product may be said to be one in which variation is influenced only by "chance causes," "chance causes" being those inherent factors always present in a manufacturing procedure and causing variations which, owing to lack of knowledge or on the score of impracticability, it is not possible to eliminate.

Many of the applications of statistical technique to industrial problems are concerned with deciding whether the variability of mean results is consistent, within defined limits of probability, with the assumption that only "chance causes" are operative, or alternatively of indicating, with a measure of probability, that on a particular occasion a cause of variability other than "chance causes" was operative.

Causes of variability associated with particular occasions have been termed "assignable causes" by some writers. These are those extraneous or occasional factors which may affect the product. In industrial practice, when the presence of such factors has been detected statistically, it is the duty of the technician to trace their precise origin and then to eliminate them.

The control chart serves to indicate the presence of extraneous causes of changes in the quality of a product, and after attempts have been made to eliminate them it serves to demonstrate whether or not they have been successful.

The construction and use of a control chart for mean results will be illustrated by utilizing the data given in Table 1.

In order to test whether the data under discussion are consistent with a bulk of fixed quality, the mean and standard deviation of such a bulk are required. They may be known from previous experience of what is satisfactory quality. Alternatively, on the hypothesis that the manufacturing processes are controlled and that only chance causes are operative, reasonable estimates can be made from the results of 5 to 10 samples each containing 5 to 10 individual results, provided that each of the samples is selected from a range of product which is subject to the operation of all the chance causes.

The variability in the average results may arise from:—

(*a*) A system of chance causes which affect the results for all samples, and
(*b*) Assignable causes which affect the results of samples differentially because they are operative occasionally.

Table 1

LAMP DATA: LIFE OF 25-WATT LAMPS AT RATED VOLTAGE (5 IN EACH SAMPLE)

1st Period			2nd Period		
Sample No.	Mean	Standard deviation	Sample No.	Mean	Standard deviation
1	2 080	464	1	1 295	440
2	1 202	575	2	2 005	435
3	1 295	422	3	2 445	580
4	1 190	406	4	1 900	345
5	987	653	5	2 570	290
6	814	487	6	1 980	510
7	2 356	521	7	1 990	445
8	1 280	639	8	1 990	315
9	1 280	318	9	1 715	385
10	1 818	555	10	1 650	460
11	1 456		11	1 935	
12	1 646		12	1 760	
13	1 060		13	2 175	
14	1 040				
15	1 234				
16	973				
17	1 128				
18	1 495				
19	2 472				
20	1 047				
21	1 465				
22	1 289				
23	1 650				
24	1 929				
25	1 199				
26	983				
27	1 148				
28	1 642				
29	1 714				
30	1 650				
31	970				

In order to obtain a measure of the variability arising from (*a*), the standard deviation is calculated from the differences of the result for each individual lamp from the average value for its appropriate sample of 5 and not from the average value of all samples. By this procedure the effect on the magnitude of the standard deviation of any variability arising from (*b*) is not included, whether or not such variability exists.

Assuming that the data given in Table 1 are those obtained when recording was initiated, the average result and the standard deviation are calculated* from

* For method see B.S.S. No 600—1935, p. 83, para. (*a*).

the first 10 samples of lamps. The average is found to be 1 430 hours and the standard deviation 575 hours.

These values are estimates of the average and standard deviation of the bulk product represented by the samples. Now if no other causes of variability appear which would affect differentially the results from sample to sample, then the average results for the samples of 5 lamps should conform to the statistical relations which govern random selections from this bulk. When the standard deviation of individuals is 575 hours, the standard deviation for the average results on samples of 5 individuals is $575/\sqrt{5} = 257$ hours.

Hence, considering the average life for the samples of 5 lamps, since the distribution of such averages will be approximately Gaussian in form only 1 result in 20 should lie outside the limits $1\,430 \pm 257 \times 1 \cdot 96$, or 930 and 1 930, and only 1 in 500 results should lie outside limits of $1\,430 \pm 257 \times 3 \cdot 09$ or 630 and 2 220, provided the data are consistent with the samples being selected at random from a bulk or bulks with average = 1 430 hours and S.D.* = 575 hours.

reducing life. For obvious reasons it is not practical to attack the second portion of the problem directly but rather first to improve life and subsequently to improve efficiency. In 1933, when the above data were obtained, preliminary investigations, involving laboratory work followed by small-scale production, had indicated that a modified manufacturing procedure would lead to an improvement in lamp life. Regular production was undertaken and data derived from the routine testing became available. Do the later results confirm that an improvement has been effected and the production controlled at the improved level?

In Table 1 results for the first 13 batches of 5 lamps, selected at random from lamps made under the new condition, are given and are shown plotted on the diagram, which is broken to illustrate a lapse of time between the two sets of data.

It is obvious that the new data depart markedly from the statistical limits derived from the old data, and an improvement in the length of life is demonstrated.

Adopting the procedure described above, new limits

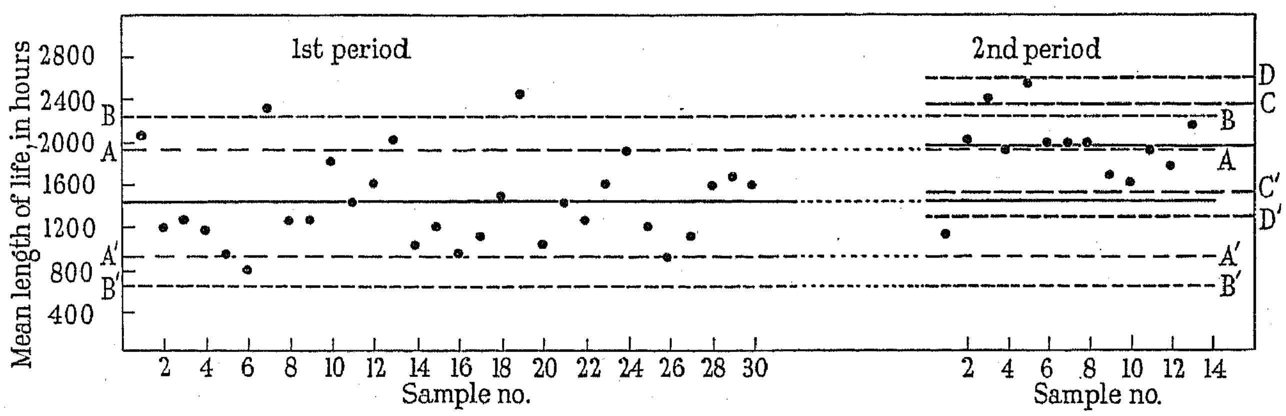

Fig. 16.—Control chart for means of samples of 5. Lamp life data.

Whether or not the test data conform with this requirement can readily be seen by constructing the control chart illustrated in Fig. 16, where the full line represents the average of the first 10 samples and the dotted lines AA′ and BB′ the 1 in 20 and 1 in 500 limits, respectively.

Referring to the chart, where a further 21 observations are plotted, it will be noted that the data conform reasonably well with the limits. This provides general evidence that the lamp life is not greatly inconsistent with the assumption that the variability in the average values is due, in the main, to the chance causes.†

The control chart, with its limits based on statistical concepts, thus provides a scale associated with probability against which to gauge whether differences in test results are due to the existence of differences in quality or to chance causes. An illustration will now be given of how the chart will indicate whether a significant improvement of the product has resulted from a deliberate change in manufacturing procedure.

In general, the quality aim of lamp-manufacturing development is to reduce variability and if possible to increase the average efficiency of light production without

CC′, DD′, have been calculated from the first 10 batches of 5 lamps selected from the new production. After some uncertainty amongst the first samples it was found that the quality of the production had settled down at the higher level, a fact illustrated by the few results plotted. Here, besides fulfilling the function of indicating whether the quality of the product is stable, the control chart has been used as a yard stick. It has provided a means for demonstrating that the improvement indicated by tests on samples actually exists and is not due to the chance of selection from an unchanged product.

A discussion of a similar example is given in B.S.S. 600,[9]* and a careful study of this would give valuable assistance to anyone making their first excursion into this field. Many similar examples will be found in Shewhart's book,[10] and another is treated in considerable detail in a paper by Dudding and Baker,[11] which endeavours to answer questions that are frequently raised by the production engineer.

In the above example the control limits have been based on the average and standard deviation of 10 samples of 5 individuals. In actual practice, as more

* Standard deviation.

† It will be seen that the results are not statistically consistent with the assumption that no variability exists other than that due to the chance causes. This actually led to an investigation of the cause.

* The pamphlet is concerned almost entirely with the statistical ideas and methods relating to control charts and gives a very full and practical account. It can be recommended as an introductory handbook to the general study of statistical methods.

data become available, it is desirable to re-calculate $\bar{X}$ and σ either to include more data or from another section of the data. Further, reconsideration of the size of each sample may be necessary. Appropriate action cannot be specified, for it will depend on the nature of each problem. The cost of testing, the degree of variability exhibited by the product, and the sensitivity required in the study of changes, will have to be taken into consideration. In this connection, some comment is necessary on the limits chosen. Shewhart, throughout his book, uses limits of 3 times the standard deviation from the mean, which corresponds to 2 to 3 observations per thousand in the tails of a Gaussian distribution. In the example described above limits corresponding to 1 in 20 and 1 in 500 respectively in the tails are shown. Whilst the wide limits, usually associated with Shewhart's choice, will increase the certainty that results lying outside them indicate the existence of change, they also increase the chance of appreciable changes in the level of the quality of the product being unobserved.

In order to minimize this difficulty limits should be utilized which correspond more nearly to the magnitude of any change it is desired to detect. This can be achieved by increasing the number of individuals in a sample. However, in most cases, this procedure would prove impracticable and uneconomic. An alternative frequently adopted is to use closer limits corresponding to a higher probability than 1 in 500, such as the 1 in 20 limits included in the above illustration. The use of these narrower limits will introduce a 1 in 20 risk of a false indication that a change in quality has occurred, and in order to avoid the effect on factory staff (referred to on page 2) the occurrence of a point outside the control limits should be treated as a warning only. Serious action should be taken only after tests on additional samples confirm the existence of a fault or after a number of such points have occurred close together. The narrower limits, however, will give an indication of changes of quality which might be missed if only the wider limits were used. For example, in the above problem, if the quality of the product were to fall 40 %, owing to some defect developing in the manufacturing procedure, the chance of an observation falling outside the wider limits (1 in 500) illustrated is still of the order of 1 in 6 tests, whereas the chance of it falling outside the narrower limits (1 in 20) is of the order of 2 in 3. That is, using the wider limits there is considerable risk of the change in quality being overlooked, whilst using the narrower limits there is a high probability of detection. These differences are of considerable practical importance when watching a continuously operating manufacturing procedure.

The discussion of a specification problem given later in the paper will assist in making clear how the differentiation of levels of quality determined by sampling involves necessarily the concept of probability. This reference to choice of control limits is only made to indicate the kind of problem which comes up for consideration. Every case can be considered on its merits, and those responsible for making decisions can be fully aware of the risks that are being taken and appraise their technical and commercial significance.

(b) Chart for Variability

Control charts, similar to that described for the means, can be made for the standard deviations or for their associated measures of variability, the coefficients of variation of samples. Such charts will not be discussed in detail; their construction and use are described in B.S.S. No. 600.[9]

An example of a control chart for standard deviations is given in Fig. 17. The data are the standard deviations of some of the separate samples of 8 specimens which were included in the general distribution of strengths of glass tubing, as shown in Fig. 11.

(c) Chart for Proportion "Defective"

(i) Use of binomial distribution.

Frequently when studying the quality of a product the chief interest will reside, not in averages or general variability, but in the proportion of articles which lie above or below a specified limit of quality. In statistical literature this proportion is usually referred to as "defective," but it must be understood that whilst the term may correctly describe the articles in question it will frequently be used when referring to an article whose quality is merely below a certain standard.

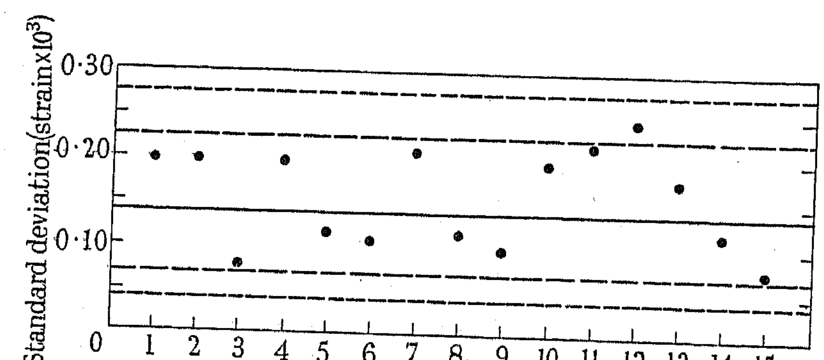

Fig. 17.—Control chart for standard deviations. Breaking strain of glass tubing (8 in sample).

When material can only be classified "good," "bad," "broken," or "unbroken," it becomes necessary to know how the chance of selection can affect the proportion of a sample falling within any class. A similar problem can arise when considering a characteristic measured on a continuous scale if the interest resides in the proportion above or below some specified limit value.

If a sample of n articles be chosen at random from a bulk containing a proportion p of defective articles, it is to be expected that the proportion of defectives in the sample will not always be exactly p, but will vary about p owing to the effect of chance in sampling.* It will suffice to state here that, if repeated samples of n are chosen from a bulk with proportion p defective the proportions of occasions on which 0, 1, 2, etc., up to n, defectives will be observed are given by the terms in respective order of the expansion of the binomial $(q + p)^n$, where $q + p = 1$. For example, a fraction q^n of the samples will contain 0 defectives, a fraction npq^{n-1} will contain 1, etc. On the basis of this relationship control limits can be determined for the number or proportion

* Professor Born illustrated the underlying principles governing this effect and they are discussed in the paper read before the Scottish Students' Section.*

of defectives in a sample within which results should fall, say 19 out of 20 or 499 out of 500 occasions if the samples are consistent with being randomly drawn from a bulk with a specific defective proportion.

Examples are given in Fig. 18 of the frequency of occurrence of errors greater than 0·5 % in the diameter of fine tungsten wires. This is used as one of the controls on this dimension (errors greater than 1·5 % rarely occur). The diameters of the wires are of the order of 0·0005 in., and 0·001 in., and about 100 and 400 individual wires form the sample in the two cases respectively.

Limits are calculated from the binomial expansion using a bulk proportion p of defectives based on the results observed, and it is seen that, in the case of the

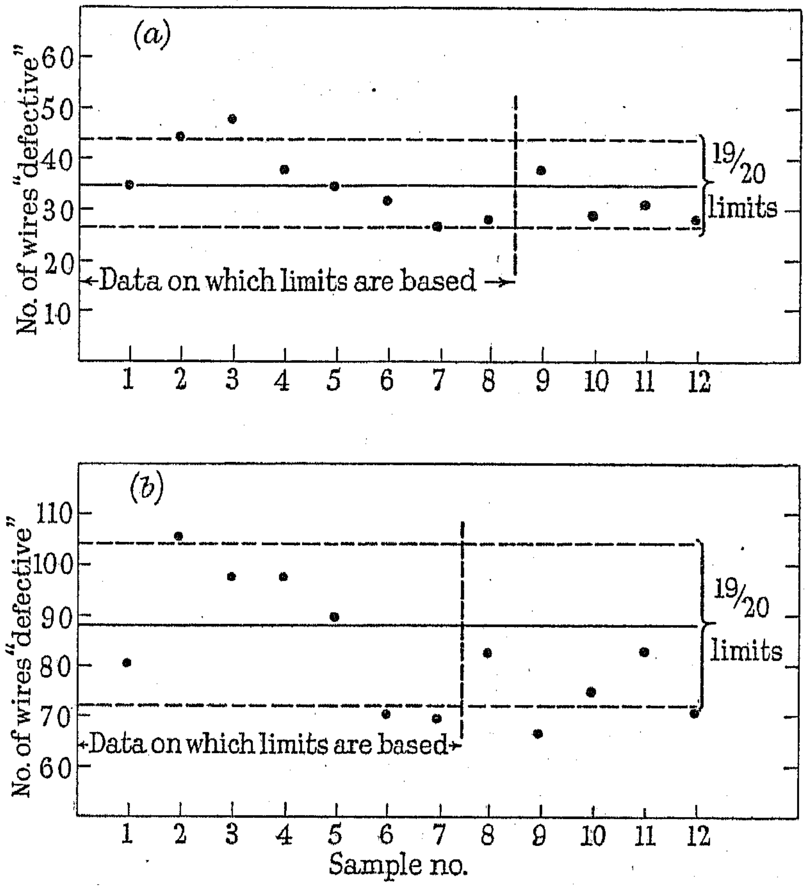

Fig. 18.—Control chart for proportion "defective." Numbers of tungsten wires with errors in size greater than 0·5 %.

(a) 15-watt and 25-watt wires (80 in each sample).
(b) Other tungsten wires (400 in each sample).

smaller wires, the variations are likely to be due to chance. For the larger wires a real improvement is indicated. Further data, which have been included in the diagram, show that these indications are correct.

(ii) Use of mean and standard deviation.

In the previous Section [(c) (i)] the appraisement of the proportion defective in the bulk has been approached by studying the actual proportion observed defective in the sample. This will often be the safest method to adopt but, in small samples, it may have certain disadvantages. One may mention, for instance, the difficulties which arise owing to the discontinuous nature of the binomial distribution. (This point is emphasized by the example discussed in the next Section.) It is natural, therefore, to ask whether, in the case of a continuously variable quantity, a better method of obtaining information about the proportion defective in a bulk could be utilized which would make use of the observed mean ($\bar{x}$) and standard deviation (s) of the sample. Whether this is so or not depends on what assumptions can be made about the form of the distribution which is being sampled.

Thus, if a product is known to follow the Gaussian distribution, and any changes likely to occur consist only in movement of the distribution bodily without any attendant alteration in the true standard deviation (σ), the sample mean will be the best statistic to study, whether information is wanted about the mean of the population or about the proportion lying beyond any defined limit whatever. However, if the mean position and the spread of the distribution may change whilst its mathematical form is likely to remain constant, then a function combining the mean and standard deviation of the sample is the best to use.

For example, referring to what has been said regarding

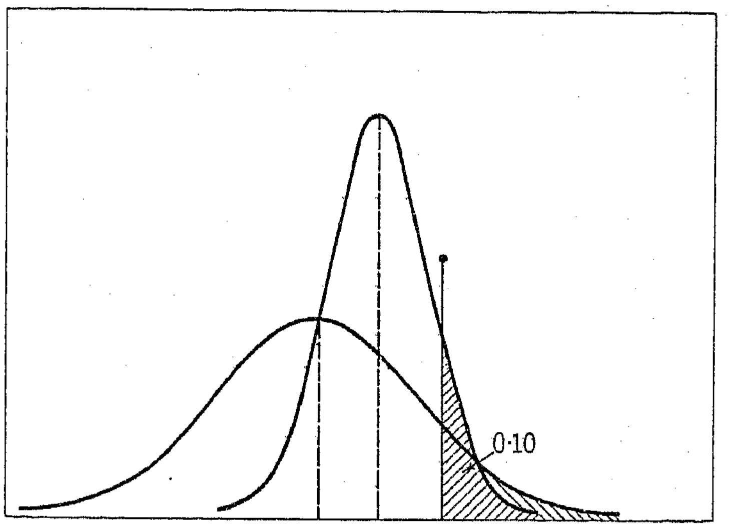

Fig. 19.—Gaussian distributions with 10 % of area above limit.

the Gaussian distribution, the proportion of items beyond a limit L depends only on the "standardized" deviation of L from the mean; that is, on the ratio of the deviation of L from the mean to the standard deviation.

Thus, for instance, all Gaussian distributions which have $(L - \bar{X})/\sigma = 1{\cdot}28$ will have 10 % of the values greater than L. The quantity $U = (L - \bar{X})/\sigma$ will, therefore, serve to connect $\bar{X}$ and σ in various bulks which satisfy the condition that they shall have the same proportions above the limit L (see Fig. 19). If a sample is available, then $u = (L - \bar{X})/s$ can be calculated from the mean ($\bar{x}$) and standard deviation (s) of the sample as an estimate of U. For a given value of U and size of sample n, it is possible to calculate control limits, corresponding to any desired probability, within which the sample values of u should fall, providing the samples conform with bulks for which U is constant. These limits, for example, could be for probabilities of 1 in 20 and 1 in 500 of results falling outside them. A discussion of the method of calculating these limits, together with a fuller discussion of their application, is given in a paper by Jennett and Welch[12] [see also Ref. (13)].

A control chart for u is shown in Fig. 20, which relates to lamp life data. The objective is to indicate that the proportion of lamps with lives below approximately 700 hours is 10 % or less. (This is, of course, the same

as controlling the proportion above approximately 700 hours to 90 % or more.) The data here are quite consistent with the hypothesis that 90 % or more of the product have a life exceeding 700 hours.

It must be emphasized that the situations in which u can be employed for the purposes of controlling the proportion below a specified limit of quality are confined to those where knowledge of the product suggests that the distribution can be relied upon to be reasonably stable in form, not only in the centre of the distribution but also out towards the tail being studied. It is dangerous to attempt to choose a limit such that, under normal conditions, the chance is exceedingly small that an individual should lie outside it, i.e. in effect to extrapolate a distribution into regions where an assumption as to its exact form is necessarily precarious, being based on insufficient data. Thus, it is not being suggested that measures such as U based on a general distribution of values have a direct bearing on the engineer's "factor of safety." Such factors are designed to meet the occurrence of very rare events which are associated with causes extraneous to the system of continuously operating chance causes which give rise to the general variability.

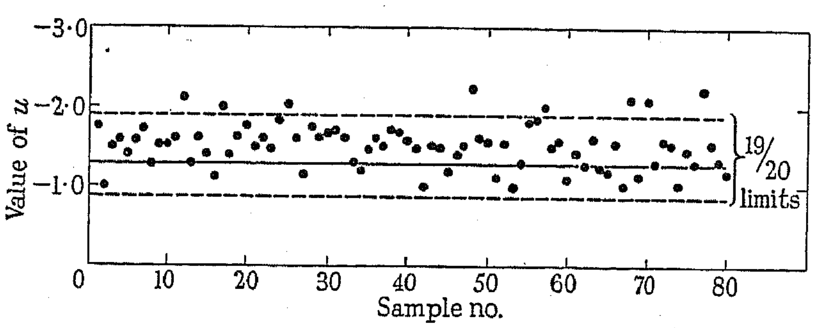

Fig. 20.—Control chart for $u = (700 - \bar{x})/s$ (30 in sample). Lamp life data.

$\bar{x}$ = sample mean.
s = sample standard deviation.

When "factors of safety" are referred to as "factors of ignorance" the description may be a really true and sound one, for the engineer who uses them does so because he humbly admits that there are limitations to his experience. Anyone who extrapolates his experience to indiscreet limits may be exhibiting a measure of ignorance dangerously exceeding that with which "factor of safety" is disparagingly linked.

The above method, which deals with the proportion defective by considering the mean and standard deviation of the sample, is likely to have a valid application for moderate excursions into the tail of the distribution, but, of course, what is "moderate" will depend on the actual problem under consideration.

(4) SPECIFICATIONS INVOLVING SAMPLING

Specifications are usually designed to establish a standard of quality agreed between manufacturer and consumer, and contain some criterion by which it is proposed to decide whether or not materials offered conform to this standard. The criterion may be defined in many ways, in terms of a mean value, or the percentage failing outside specified limits, etc. It will be clear from what has already been described that, if sampling is involved, then whatever the specification criterion, samples, chosen from bulk supplies whose measures of quality correspond to widely different values of the mean and spread in the characteristic specified, may yield the same value of the specification criterion. That is, the influence of chance is such that a single sample may lead to material being accepted which is below the standard the specification was designed to establish and, contrarily, chance may lead to the rejection of "satisfactory" material.

The probability of material being rejected by the specification will depend on the actual level of the quality characteristic concerned relative to the level required by the specification, and on the degree of variability which would be experienced by repeated sampling from that material in accordance with the specification. The variability referred to here will depend on the variability exhibited by the material in respect to the characteristic measured and on the form of the specification.

Assuming that a limit value for a quality characteristic of a sample is defined to determine whether a bulk supply is accepted or rejected, then clearly, if the quality characteristic of a bulk supply approximates to the value defined for a sample, the material will have about a 50 % chance of acceptance or rejection. For example, if a product is rejectable when more than 10 % of a sample is "defective," then a bulk product containing 10 % "defectives" will have about a 50 % chance of acceptance or rejection, because if sampling were repeated many times one half of the samples would contain less than, and the other half more than, 10 % "defectives."

As the quality level of a bulk supply is raised above the sample criterion the chance of acceptance is increased and the chance of rejection reduced. On the contrary, as the quality level of a bulk supply falls, so the chance of acceptance is reduced, and of rejection increased. Hence, when considering the specification criterion for a sample there is essentially some conflict between the points of view of manufacturer and consumer. If the assumption be made that the manufacturer knows the general level and spread in quality of his product, he has then to decide what chance he can take of having material of his normal level of quality rejected. He will, in general, desire the specification criterion for a sample to represent a level of quality lower than that he can maintain, in order to reduce his risk, say, to 1 in 20 or lower.

However, if the consumer appreciates the implications of a sampling specification, he will realize that this lower level of quality represented by the sample criterion will, of necessity, mean that there will be appreciable risk that he will accept material lower in quality than that of the manufacturer's product considered above.

Hence, once a sample criterion is fixed it will divide material concerned into three general classes:—

(i) Material of high quality which will be rejected on rare occasions.
(ii) Material of low quality which will be accepted on rare occasions, and
(iii) Material of intermediate quality which may or may not be accepted.

If a chance of rejection and acceptance can be agreed to represent a practical interpretation of the word "rare," such as 1 in 20, then the zones (i), (ii) and (iii) referred to can be defined more explicitly.

The level of quality for a bulk supply for which there is a 1 in 20 chance of its being rejected may be described as "the manufacturer's safe level," and the level of quality for which there is a 1 in 20 chance of its being accepted may be described as "the consumer's safe level."

The region of product quality between these two levels is a region of uncertainty, and its range is a practical indication of the efficiency of the specification.

To illustrate the foregoing discussion Fig. 21 has been prepared based on the following specification criterion:—"That not more than 10 % plus one article, fractions counting as whole numbers, shall have a test value less than a defined value, the number of individuals in the sample being 5 % of the bulk, provided not less than 10 articles be tested."

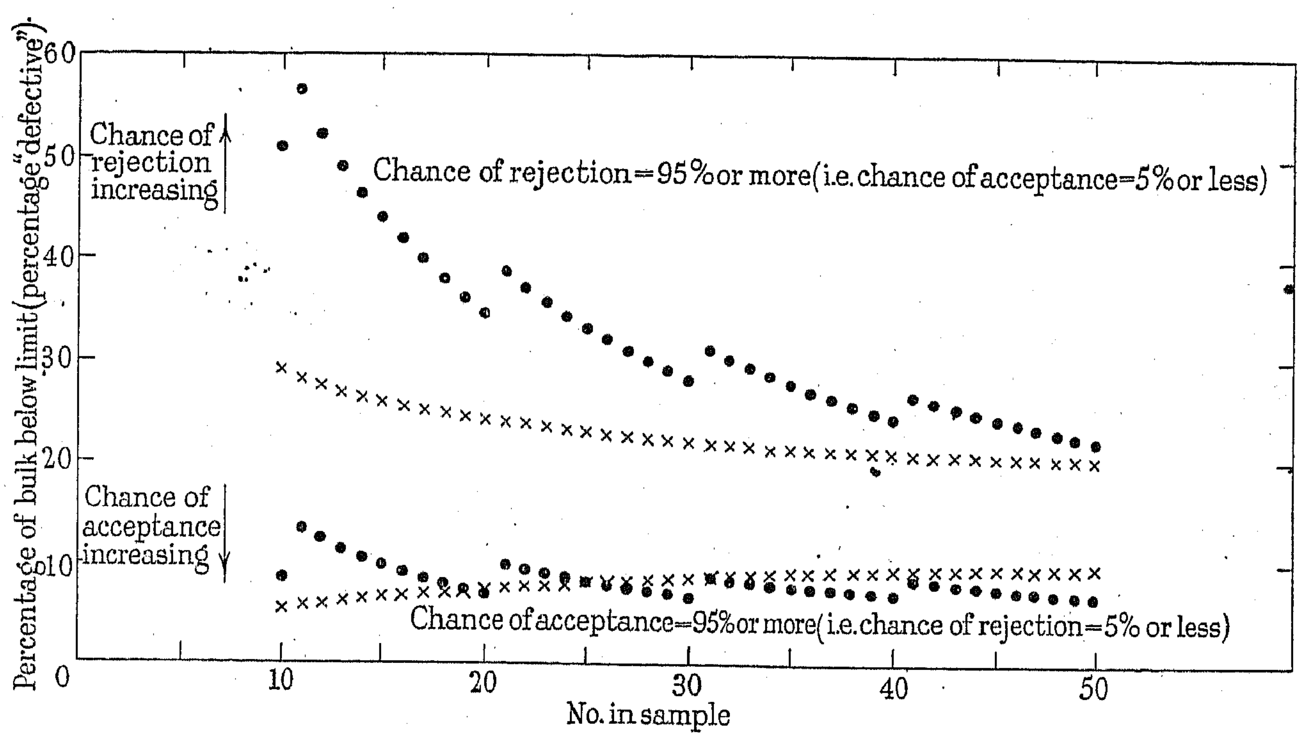

Fig. 21.—Implications of a specification.

● ● Clauses based on percentage "defective" in sample.
× × Clauses based on average of sample.

The sampling clause permits any number of individuals greater than 9 in the sample, and the permissible number of individuals in the sample which can have a test value below the specification value changes discontinuously, thus:—

From 10 articles	2 can be below specification value.
From 11 to 20 articles	3 can be below specification value.
From 21 to 30 articles	4 can be below specification value.

and so on.

The dots shown in the Figure indicate, for each size of sample, the proportion of articles below the specification value which can be present in bulk supplies for a 1 in 20 chance of acceptance and rejection, respectively. The upper set of dots represents the consumer's safe level, and the lower set the manufacturer's safe level. For example, consider samples of 15. If 44 % of the articles in the bulk were defective, then only once in 20 selections would the product be accepted, because not more than 3 articles in the sample were defective. On the other hand, if 10 % of the articles in the bulk were defective then only once in 20 selections would the product be rejected, because more than 3 articles in the sample were defective.

It is clear that this type of specification clause maintains, approximately constant, the chance of rejection of material having 8 % below the specification value, whatever the size of the sample. However, it will be noted that, when the size of sample is small, the proportion of "defectives" in the bulk can be quite large before the chance of acceptance is reduced to as low as 1 in 20, but the distance between the two sets of dots rapidly diminishes as the size of the sample increases.

The clause already considered involves no knowledge of the mean value and spread in the quality of the product. However, suppose it were known that for this product the distribution can be considered as Gaussian; that the spread is closely constant; but that the average value may change. The change in the average value will then determine the proportion in the bulk supply below a fixed level and, hence, the specification can be drawn up in terms of the average value of the sample. (This state of affairs is not infrequently met in practice.)

Under the conditions here formulated, a limit value can be specified below which the average value of the sample should not fall, from which it is possible to define the manufacturer's and consumer's safe levels. Such levels appropriate to a clause which does not appreciably change the specification from the manufacturer's point of view, are indicated in the Figure by crosses. It will be noted that the discontinuous nature of the quality levels disappears, and that the difference between them is considerably reduced, indicating that the efficiency of the specification is improved.

In all cases, when specification clauses are under consideration, an investigation on the lines of the foregoing is essential, if their real implications to both manufacturer and consumer are to be appreciated.

Finally, close study of the problems arising in the course of drawing up intelligent specifications will emphasize the very considerable advantages to be gained by the adoption of a system under which the manufacturer guarantees to maintain his product at an agreed standard, his guarantee being founded on evidence, available to an independent standardizing authority, that efficient control of processes and products is continuously maintained.

Table 2

TEST RESULTS FOR PRODUCT OF MULTI-HEAD MACHINE

Side of machine	Left						Right					
Head number	1	2	3	4	5	6	7	8	9	10	11	12
Individual values	31	28	25	30	23	31	33	34	35	27	37	31
	33	36	30	30	28	27	36	29	35	36	29	39
	29	35	28	29	31	28	23	31	29	30	32	45
	31	29	31	33	32	32	43	39	35	23	42	36
	36	31	31	33	27	28	41	35	32	37	41	36
	34	39	29	37	31	31	33	34	35	39	32	39
	31	35	31	36	35	37	23	31	31	53	33	36
	24	33	36	45	23	43	33	27	39	38	37	51
		27	34	34		46	36	28	36	34	34	32
			38				25	34	27	39	37	
			35				32	36	39	35	36	
							37	34	32	29	41	
							39	33		43	32	
										38		
Head means	31·0	32·6	31·6	34·1	28·7	33·7	33·4	32·7	33·7	35·8	35·6	38·3
Side means	32·0						34·8					
Grand mean	33·6											

(5) ANALYSIS OF VARIANCE

As a result of using control charts, coupled with careful consideration of the underlying principles involved when interpreting them, it will be realized that the process is basically one in which variability arising from different sources is compared. The need will be felt for a technique by which total variability may be apportioned to different sources in a manufacturing procedure, and assistance provided for estimating the relative importance of the contributions from such sources. It is at this stage that the engineer will appreciate the utility of the elegant statistical procedure known as the " Analysis of Variance " which was developed by Fisher.[14, 15]

The square of the standard deviation, i.e. the mean-squared deviation, is known as the " variance," and has the property that contributions to it from various independent sources are arithmetically additive. In the analysis the total variance of a set of data is divided into amounts assignable to specific and chance causes. Statistical theory provides a means for estimating on a

probability scale whether the variability attributed to a specific cause arises solely from chance causes or not. The following example of the analysis of variance is described in some detail because it illustrates a very important general principle which, in the opinion of the authors, can scarcely be over-emphasized.

tion is that the data for all 12 heads are subject to the same system of chance causes. The analysis would indicate that No. 5 alone is affected by a cause other than the general system of chance causes. However, knowledge of the construction of the machine throws suspicion on the validity of this assumption and conclusion,

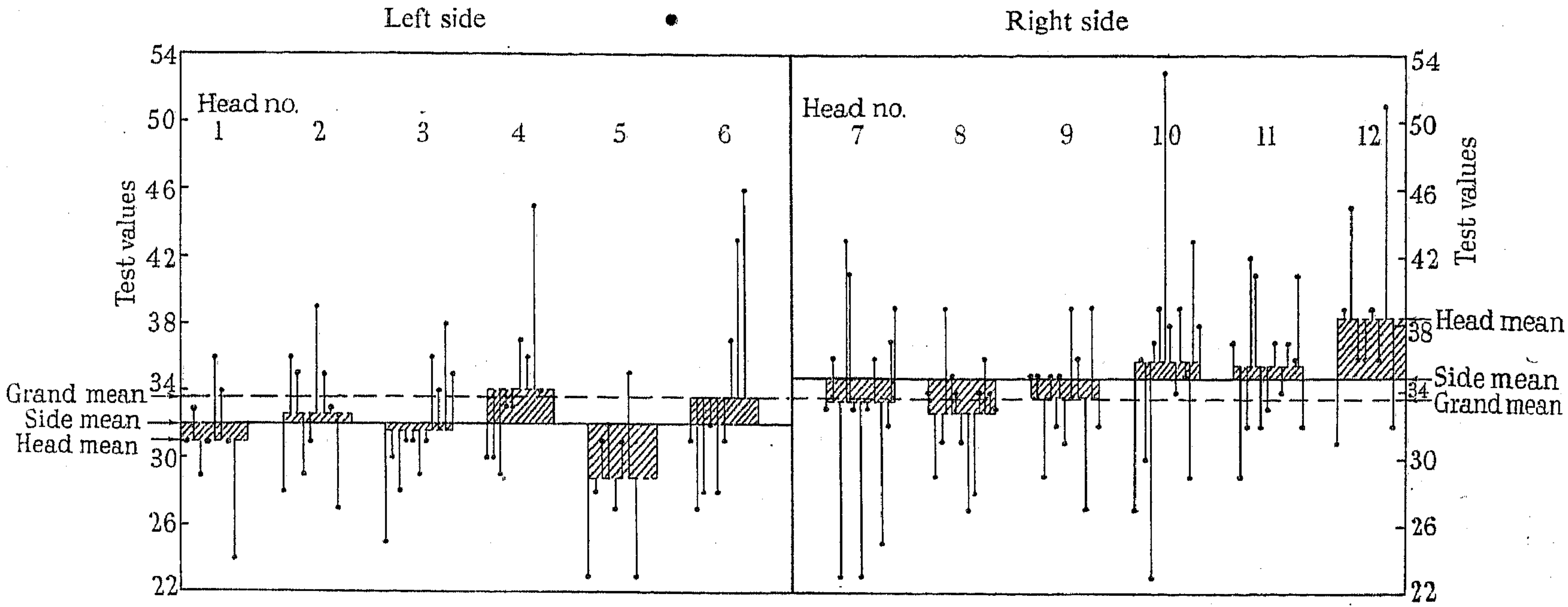

Fig. 22.—Test results for product of multi-head machine.

The data given in Table 2 and illustrated in Fig. 22 are the test results obtained some time ago on the product of a machine making articles on 12 different "heads." An inspection, by the engineer in charge, of the results from the 12 heads naturally suggested that head No. 5 was producing poor work and needed some

because an essential portion of the driving mechanism consists of two parts, one part being common to the six heads constituting what may be conveniently described as the left side of the machine, and the other part common to the six heads constituting the right side. The engineer might be expected to take the next step of

Table 3

Analysis of Variance

Source of variation	Sums of squares of deviations	Degrees of freedom	Mean variance	Z	Significant levels of Z	
					1 in 20	1 in 100
(*a*) Differences within heads	3 139	116	27·1			
(*b*) Differences between heads within sides	392	10	39·2	0·18	0·32	0·45
(*c*) Differences between sides	233	1	233	1·07	0·68	0·97
Total	3 764	127				

Note: For (*b*), $Z = \frac{1}{2}\log_e \frac{(39\cdot 2)}{(27\cdot 1)}$

For (*c*), $Z = \frac{1}{2}\log_e \frac{(233)}{(27\cdot 1)}$

attention. Further, a statistical analysis, following the principles underlying the control chart for mean results by which the variability exhibited between the mean results of the 12 heads is compared with the variability exhibited among the results from each head, would confirm this impression. As a result, the action decided upon would be to service head No. 5. So far, the assump-

calculating the mean results for the left and right sides respectively; to note that they differ, and that head No. 5 is associated with the lower "side" mean.

The questions will arise: Does the difference between the two side means indicate a fault in the associated mechanisms, and does head No. 5 need attention?

A formal statistical analysis following the technique

of the analysis of variance will give sound guidance and confidence in answering these questions. In Table 3 the total variability of the 128 results has been divided into three parts, (*a*) the amount of variability which is associated with the product of any one head, (*b*) the variability which is exhibited between the products of the heads on the same side of the machine, and (*c*) the variability which is contributed by the two different halves of the machine.

The variability (*a*) is that attributed to the system of chance causes, and (*b*) and (*c*) may be described as the variabilities due to assignable causes, because there are technical reasons for attributing them to particular portions of the mechanism. The chance variation would give rise to some variation in (*b*) and (*c*), even if the different parts of the machine had no influence. The magnitude of the variabilities (*b*) and (*c*) can be compared after allowance has been made for the contribution of the chance causes (*a*).

The procedure is summarized in Table 3. Here are shown the values of a quantity usually denoted by Z, which are calculated from the variabilities to be compared. In addition, from published data,[12] values of Z are given which might be expected only 1 in 20 times and 1 in 100 times if the results for the separate heads were random samples from bulk supplies subjected only to the operation of the chance causes.

The relatively high value of Z (1·07) for the "between sides" contribution indicates that this is significant, whereas the low value (0·18) for the "between heads, within sides" contribution indicates that this may have arisen from chance causes. In other words, the level of quality of the product is different for the two sides of the machine, but, on any one side, the six heads are producing work of substantially the same quality. There is no longer strong evidence that head No. 5 is producing work inferior to the other heads with which it is associated. The practical result of this is that something common to all the heads on the left side and not associated with those on the right side should first receive attention, and the individual heads not be disturbed. Actually, as a result of correct analysis, a fault was discovered in the mechanism associated with the left side, and, after correction, the quality of the product of the whole machine rose to that of the right side. No attention was given to head No. 5.

Without such a formal analysis based on statistical principles any technical man would almost certainly have given attention to head No. 5, and, unfortunately, because the low value for the product of head No. 5 was due to chance, it is highly probable that later data would have convinced him that attention had had the desired effect. On the other hand, without the knowledge of the operation of the machine a statistician could not have been expected to have gone further than the first stage of the analysis in which head No. 5 compared unfavourably with the other eleven heads.

In practice more complicated problems arise, but after experience with some simple examples the ability to apply the principles underlying this procedure above referred to will be acquired and its value properly appreciated.

(6) FURTHER EXTENSIONS OF STATISTICAL TECHNIQUE

The principles which form the foundation of the various techniques illustrated in the foregoing Sections are capable of considerable extension.

One of the most important is probably that in which it is desired to know whether or not different measured characteristics of a product are essentially related. The existence of any such relation can often be used to avoid destructive testing at various stages of the manufacture of a product, offering considerable economies in the cost of maintaining effective quality control.

Further, it is also necessary to make due allowance for any relation between observed characteristics in order to draw correct conclusions from the study of data.

Examples of the use of statistical technique in more complicated problems are contained in various papers of the Supplement to the *Journal of the Royal Statistical Society*. Many of the most valuable are based on data derived in the course of agricultural research, but a study of these is unlikely to be useful without considerable experience with simpler problems of the type described in previous Sections.

(7) GENERAL

The foregoing review cannot, by reason of limitation of space and time, do more than provide an introduction to general principles and indicate a line of development that can be followed when applying probability theory to the everyday problems arising in a manufacturing industry.

Throughout the treatment it will be realized that fundamentally the assumption first made is that the variability exhibited by the product sampled arises entirely from a system of chance causes. The test data derived from sample groups of individuals chosen with a knowledge of the manufacturing procedure so that each sample is likely to be equally subject to the system of chance causes are then examined in the light of the primary assumption, using the theory of probability as a guide. Lack of statistical consistency in the results is an indication that variability, external to the system of chance causes, exists.

Technical knowledge of the manufacturing processes has then to be used to suggest the origin of this variability, and recourse subsequently made to statistical technique to confirm or refute the suggestion. This is the fundamental pattern on which the technique is built.

In the Introduction attention has already been drawn to the advantages which will accrue to the engineer who takes the trouble to acquire the technique. It is fitting to conclude by drawing attention to two important principles which must not be overlooked. The successful operation of a manufacturing procedure demands considerable experience and detailed knowledge of machines and processes. If this experience is associated with specialized knowledge of physics and chemistry few will dispute, at the present time, that the engineer so equipped is better able to fulfil his function in industry than one depending solely on engineering knowledge and experience. Similarly, if to these accomplishments the engineer can add a working familiarity with the principles of statistics he will still further enhance his value to

industry. The use of the statistical technique alone cannot solve problems demanding a knowledge of physics, chemistry, and engineering, but it can serve as a powerful aid when drawing conclusions from technical data.

An example has been given where the experienced engineer lacking statistical knowledge, and the statistician lacking practical knowledge, would probably have come to the same erroneous conclusion. Correct diagnosis of the difficulty in the factory was only possible by a combination of the attributes of the two. The necessity for this combination cannot be over-emphasized.

Finally, a warning should be sounded against any inclination to believe that acquirement of the technique so inadequately described in this paper can be achieved by listening to papers on the subject or by reading text-books. No one has become a good pianist merely by reading Tobias Matthay's book "Muscular Relaxation Studies," but many have done so by combining concentration of mind with practice of the technique there described. The practice of statistical methods, associated with a keen appreciation of the principles involved, will alone give the engineer command of this valuable industrial tool.

The authors would like to take this opportunity of thanking Professor E. S. Pearson and Dr. B. L. Welch of the Department of Statistics of University College, London, for many opportunities to discuss problems of mutual interest during recent years.

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WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. C. E. R. Bruce: I should like to point out that an answer to the question propounded by the authors in the first paragraph of their Introduction was attempted in a paper published by the E.R.A. in 1927, in relation to the testing of circuit-breakers.*

The number and magnitude of the errors sometimes committed in the scientific and technical Press through lack of the application of even elementary statistical conceptions is surprising. For example, Norinder† has emphasized the agreement between the distributions of lightning currents found by him and those obtained from magnetic-link data. In this he has been followed by such authorities as Müller-Hillebrand‡ and McEachron and McMorris,§ who have quoted this agreement without comment. In so doing these writers entirely ignore the important difference between the methods by which these two sets of values were obtained; for whereas Norinder has calculated the current in each of the individual strokes of a flash of lightning, the magnetic link records only the maximum current in the complete flash. As there are anything from 1 to 20 or 30 strokes in a flash, the average number being 3 or 4, the two distributions should not agree at all, but that obtained from the magnetic links should be approximately equivalent to the distribution of the maxima in groups of 3 or 4 selected at random from Norinder's data.* The agreement between the two distributions as presented is thus seen to be disconcerting rather than satisfactory. The cause of the discrepancy will be dealt with in a forthcoming E.R.A. paper on the mechanism of the lightning flash. McEachron† has even gone further and compared the magnetic-link data obtained on power lines with that obtained from links on the Empire State Building, one of which had received as many as 19 flashes, and others 11, 8, 6, . . . and so on, while the links recording two of the largest currents had been subjected to an unknown number of flashes, so that the resulting distribution curve is quite meaningless as it stands. In another paper he has suggested,‡ on what

* E. B. WEDMORE, W. B. WHITNEY and C. E. R. BRUCE: *Journal I.E.E.*, 1927, **65,** p. 913.
† *Journal of the Franklin Institute*, 1935, **220,** p. 85.
‡ *Bulletin I.R.E.* (Rumanian National Institute), 1936, No. 109.
§ *General Electric Review*, 1936, **39,** p. 490.

* For an example of distribution curves related in this way, see *Journal I.E.E.*, 1927, **65,** p. 916, Fig. 2; comparing the curve for $n = 5$ (say) with the original distribution ($n = 1$).
† *Journal of the Franklin Institute*, 1939, **227,** p. 205, Fig. 37.
‡ *Electrical Engineering*, 1938, **57,** p. 510.

seems to me quite insufficient grounds, that the storms affecting the overhead lines which he discusses were of different types, some of which contained only "single-stroke" flashes, some only "multiple-stroke" flashes, and some a mixture of both. The data for two of the years he discusses are almost exactly what one should expect as the result of random selection from one type of storm containing the proportions of single and multiple strokes usually met with in British, American and South African thunderstorms. Thus, though different types of storm may occur, the data so far presented cannot be regarded as establishing this.

The first of the above examples illustrates the necessity, stressed by the present authors, for a thorough understanding of the data before statistical methods are applied.

I shall only mention briefly some further applications of statistical methods made by the E.R.A. in recent years, as these will form the subject of a forthcoming paper. In further work on the rating of circuit-breakers it was shown that 3-phase tests may be inadequate to establish the rating of a circuit-breaker which shows irregularity of operation in repeat tests, unless the test voltage is quite markedly increased to ensure that the maximum liberation of energy to be met with in breaking the worst fault conditions has been experienced during the tests. The results obtained were surprising, and seemed to offer a probable explanation of some of the circuit-breaker failures which had occurred up to that time (1933). This investigation has also been found applicable to similar investigations on contactors.

The procedure in the experimental determination of conditions of flameproofness has also been subjected to scrutiny, the result being that the number of tests regarded as necessary for this purpose has been considerably increased, and that statistical methods of assessment have been applied to the results. I cannot find evidence in work published elsewhere that this need has yet been realized, and the occurrence of either one or two explosions of the explosive mixture within the flameproof tank which do not cause an ignition of the surrounding explosive atmosphere is apparently still regarded as adequate as a test of safety of the flange gap. In fact, however, the approach to "safety" as the flange gap is reduced is in many cases a comparatively slow one, and the range over which an explosion of the external atmosphere may or may not occur quite a wide one, so that the occurrence of even as many as 10 or 20 successive non-ignitions of the external mixture with a given flange gap is not an adequate criterion of safety, the latter requiring in addition some form of statistical estimation. It may be noted in passing that this work has led to the introduction of statistical methods of assessment of test data into other investigations made by the Safety in Mines Research Board.

Many investigations depend on the estimation from a sample of the maximum or minimum value of the quantity investigated likely to be met with in practice,* to which estimate a factor of safety can then be applied with some security to cover other contingencies. In this connection I should like to ask the authors whether many of their sets of data (populations) are sufficiently extensive to determine whether or not the type of departure from the Normal Law found by Hulme and Symms* applies to any of such data in cases in which the Normal Law is approximately followed. These workers found a much higher proportion of very high and very low values of the deviation from the mean than would be expected if the data were distributed according to the Normal Law, and they mention quite a good reason for such a deviation. It seems to me likely that the complete distributions of such articles as those discussed in Section (5) of the paper might well be of the form found by Hulme and Symms.

This question of the tails of the distribution curve is only one aspect of the general question of the general form of these curves in different cases, which it seems to me the authors are in an excellent position to analyse. From an intimate knowledge of the processes of manufacture it should be possible to say something of the factors which determine the general shape of the distribution into which the manufactured articles fall. I should be interested to hear the authors' views on this question.

A rapid check as to whether a set of data is distributed according to the Normal Law or not, and some idea of the extent of the departure therefrom, can be obtained by plotting the data on probability paper. As this process has been described in several papers† it is sufficient merely to mention the method.

Though the above may appear to over-emphasize the lack of universality of the Normal Law at the expense of its great advantages, it is well to keep in mind its limitations; otherwise the impression easily takes root that it is the alpha and omega of frequency distributions, just as some engineers come to believe that the frequency of an oscillating circuit is given completely by $1/\sqrt{(LC)}$.

The authors mention a very important feature of the normal distribution, namely that as the size of the sample selected from non-normal distributions is increased, the distribution of the means of the samples approaches closer and closer to the normal. A good illustration of this property is afforded in the early E.R.A. report already mentioned, in which the original distribution is very skew indeed.

Mr. W. J. C. Fletcher: If the examples given in Figs. 3–15 are studied, it will be observed that in some cases, e.g. Figs. 7, 13 and 15, the distribution curves differ from the Gaussian form in a special way; that is, these curves tend to rise slowly from the left, and to descend more abruptly to the right, of the "mean value."

It would appear that this tendency is a natural one, under the given circumstances, and has some connection with the efficiency of the processes used in manufacturing the products to which the curves are referred.

Thus, in Fig. 13, supposing the process was such that a large proportion of the primary cells converted nearly all of the chemical energy contained in the ingredients into electrical energy, then the "mean value" would be near the maximum possible value of watt-hours, and the right-hand half of the Gaussian curve would be curtailed. On the other hand, values of watt-hours less than the mean value are always possible; hence the left-hand half of the

* See, for example, *Journal I.E.E.*, 1927, **65**, p. 913.

* *Monthly Notices of the Royal Astronomical Society*, 1939, **99**, p. 642.

† See, for example, A. F. DUFTON: *Philosophical Magazine*, 1930, **10**, p. 566, and E. H. SELWYN: *Proceedings of the Physical Society*, 1938, **50**, p. 914.

curve approaches more nearly to the true Gaussian distribution curve.

I should be glad to have the authors' comments on this suggestion, and on the possibility of developing a measure of the efficiency of a process (where such efficiency is not already known by other methods) by an examination of the distribution curve of a characteristic exhibited by the product.

For example, in a complicated process, like paper-making, it is difficult, if not impossible, to calculate theoretically the maximum possible tensile strength of the product. Tests on a large number of specimens would reveal only the maximum strength recorded, but an examination of the distribution curve of these test results may indicate how much greater strength would actually be possible if chance optimum conditions could be more nearly approached by design.

Mr. P. Good: It may be of interest to place on record some of the reasons which led to the formation of the Committee of the British Standards Institution which is referred to early in this paper.

At one time it was anticipated that the free use, on the sole responsibility of the producer, of an authoritative mark to indicate conformity to a standard would be satisfactory in the sense that any serious misuse would be unlikely to occur, and if it did occur, could be dealt with readily by ordinary processes of law. Investigation showed, however, that the use of such marks must be on a controlled basis in order to provide reasonable security for the honest user, and the development of a satisfactory method to be adopted to secure effective control did not prove easy.

It was not until the subject dealt with by the authors attracted our attention some years ago that a satisfactory system of control seemed possible. A 100 % guarantee of uniformity in the commercial production of any article is impossible, but by the scientific study of the variations that occur it is possible to assess their relative importance so as to bring these variations under control. Under such conditions a hall-mark of quality has a real significance, and with the help of several expert workers in this field, including one of the authors, the basis of the present principles of control of the B.S.I. certification was established. Several years' experience has confirmed the soundness and practicability of those principles.

To those concerned with specifications for materials or products the analysis of the difference between a specification which bases rejection or acceptance on the results of tests on a few samples and one which is based on the average value of a large number of samples is of primary importance. The authors have shown how, by a slight modification to the ordinary method of sampling, a greater assurance is given to the consumer that the material conforms to the specification. This modified method does not add to the difficulties of the manufacturer.

Several British Standard Specifications, notably the lamp specifications, have been based, with the assistance of the authors, on the methods developed and advanced in this paper.

A study of the subject presented in this paper is recommended to anyone concerned with the industrial production of almost any commodity.

Dr. W. G. Radley: One of the problems confronting the engineer who is making a series of measurements is that of determining when his accumulated data have become statistically stable. Until such stability is reached neither the most probable value of the quantity being observed is known, nor can the likelihood of future measurements lying within specified limits be accurately assessed. A technique for testing the stability of accumulating data as observations proceed is in use in the laboratories of the Post Office Research Station. Specially ruled probability paper is used, and on this is plotted the percentage of the total number of observations exceeding certain arbitrarily chosen values. A simple example will make the use of this method clearer. During an investigation concerning teleprinters, it was

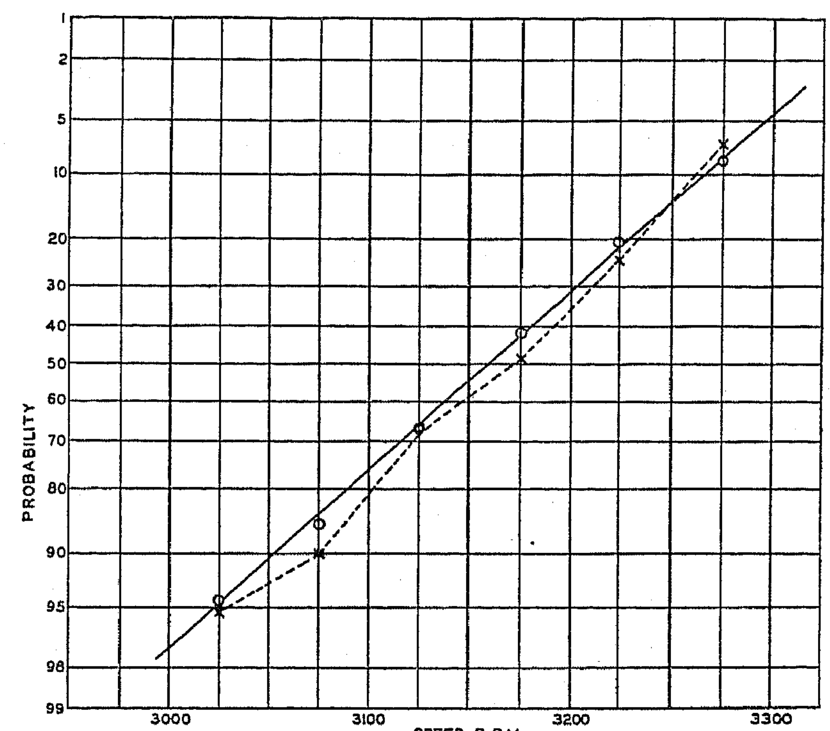


Fig. A.—Test for stability of data.
× 19 motors.
○ 36 motors.

required to find the chance of the driving motor failing to attain a speed of 3 000 r.p.m. under certain conditions of load and supply voltage, and 19 motors were taken at random and tested under these conditions. The percentage of the total group having observed speeds exceeding 3 050, 3 150 r.p.m., etc., are plotted as crosses in Fig. A. The irregularity of the dotted line joining these crosses indicates instability of the data. The observed speeds on a further 17 motors were therefore added to those previously obtained, and the combined results are plotted as circles in Fig. A. These circles lie on a straight line, indicating that the distribution of values about the mean (3 158 r.p.m.) is according to the Gaussian law and that, if further observations were made, the distribution would remain unaltered. σ was found to be 75 r.p.m., so that, considering for convenience the probability given on page 3, i.e. that of the motor speed being outside the limits of $\pm 1 \cdot 96\sigma$, there is a $2 \cdot 5$ % chance of the speed being below 3 011 r.p.m. Any type of stable skew distribution would similarly have been represented as a straight line on logarithmic probability paper, and the same test for stability applies.

In many practical cases connected with telecommunications engineering, examination of a series of results indicates that values do not follow the Gaussian form of distribution about a mean. Actually the statistician recognizes the Gaussian distribution as only a special case among many types of distribution, including commonly-occurring skew distributions. As the distribution curves are generated by well-known mathematical formulae, the proportion of observations lying outside any set limits can be calculated once stability of data has been attained and the type of distribution is known.

The tests described above are easy to make. If they are applied to many of the examples given in Figs. 3 to 15 of the paper, it will be found that the data presented are unstable. Unstable data can, however, be analysed by methods which have been developed, notably by Scandinavian actuaries. The more elaborate methods of the statistician are unlikely to appeal to the engineer, but much useful information as to sampling errors and as to variations (i.e. standard errors) can be obtained by plotting the data on Poisson probability paper.

Mr. P. d'E. Stowell: As an engineer engaged in electricity supply I think that it is a pity that my section of the profession does not follow the example of telephone engineers by using statistical and probability methods for the solution of problems of demand and diversity, which are both largely dependent upon variations brought about by chance.

I entirely agree with the authors that, in the interests of progress, the statistical tool should be brought more and more into the realm of electrical engineering; but in my opinion this aim would be better advanced by considering applications which are fundamentally electrical in character.

Wedmore and Flight in their paper on "Voltage Variations at Consumers' Terminals"* suggested an application on which I think there is plenty of scope for further research with a view to a possible alteration of the permissible limits of variation, or at least in an endeavour to specify these limits upon a statistical basis. For instance, statutory limits of $\pm$ 6 % are all very well, but it may be taken for granted that it is impossible to comply with them strictly, whereas if the maximum permissible coefficient of variation were fixed on a statistical basis at, say, 2 %, the same order of result would be obtained under normal conditions and allowance would also be given for abnormal conditions. To assist a study of this subject I have designed (but have not as yet made) a recording meter which would provide an automatic analysis of the variation.

Another application is to railway power-supply problems, in which, of course, the power demand fluctuates continually over a wide range. In 1935 I found that in a typical case these fluctuations could be handled by statistical methods, and the power-supply plant for a new electric railway was subsequently proportioned on this basis. W. Fordham Cooper† has pointed out that similar methods are applicable to electric tramway systems.

As a final suggestion, it may well be that as we become more statistically minded the conceptions of maximum demand, load factor, etc., will eventually be replaced by the statistical coefficient of variation of the demand about its mean. This has a lot to commend it, and standard deviation (and so its derivative, coefficient of variation) is a very familiar concept to electrical engineers by reason of being a root-mean-square function. In this way it would be possible to devise a tariff which would have the same effect as present tariffs in encouraging a constant load and so a high load factor, by charging for variability of the load, but which would not impose penalties for abnormal demands arising out of such things as unusual weather conditions and therefore produce extra revenue for the supply authority without in general any corresponding increase in the cost of supply. On this basis too, diversity can be treated in mathematical terms, for it is readily possible to add two or more varying quantities specified in this way and assess the probable variability of the sum.

Dr. B. L. Welch: Without entering into calculations which involve more than simple arithmetic and the ability to use a mathematical table, the authors clearly expound the basic ideas from which derive a great many statistical applications, whether to problems which arise in working to internal specifications in the factory, in attempting to meet the requirements of external specifications or in developing new products in the laboratory. It will be noted that a prominent place in this discussion is held by the so-called Gaussian or "normal" curve, illustrated in Fig. 2. It has sometimes been held to be a weakness that so much of statistical theory depends upon this curve, and this objection has been used as an argument against employing any statistical methods of the type described in the paper. It has been pointed out that physical characteristics are often distributed in a fashion which cannot, even approximately, be represented by the Gaussian curve. This may be true, although in the examples given in Figs. 3–15 the representation by Gaussian curves would not appear to be far-fetched. The question whether, in any particular instance, the approximation is close enough depends, of course, upon what kind of conclusion one wishes to draw. It cannot be answered by a plain "yes" or "no." It is in this connection that I should like to make a short contribution to the present discussion.

In Section (2) and Fig. 2 of the paper it is noted what percentages of the Gaussian distribution lie outside certain multiples of the standard deviation from the mean. For instance, the chance is 1 in 20 that an individual will lie outside the range from $(\overline{X} - 1\cdot96\sigma)$ to $(\overline{X} + 1\cdot96\sigma)$, and 1 in 500 outside the range from $(\overline{X} - 3\cdot09\sigma)$ to $(\overline{X} + 3\cdot09\sigma)$. If the distribution is not Gaussian the proportions outside these limits will differ from 1 in 20 and 1 in 500 respectively, and in taking these figures some error will be committed. In absolute value the error involved in taking the frequency outside the range from $(\overline{X} - 1\cdot96\sigma)$ to $(\overline{X} + 1\cdot96\sigma)$ to be 1 in 20 will be greater than that involved in taking the frequency outside the range from $(\overline{X} - 3\cdot09\sigma)$ to $(\overline{X} + 3\cdot09\sigma)$ to be 1 in 500. Proportionately, however, the situation will in general be reversed. The latter error expressed as a proportion of 1 in 500 will be larger than the former expressed as a proportion of 1 in 20.

* *Journal I.E.E.*, 1935, **76**, p. 686.

† *Ibid.*, 1938, **82**, p. 94.

Relatively speaking, the further one goes out into the tails of the distribution the more important become the errors due to an incorrect assumption of "normality." Now usually the only information available as to the form of the distribution is derived from results such as those shown in Figs. 3–15. From such results it may be possible to deduce that the Gaussian curve follows sufficiently well the main body of the distribution, but seldom will there be enough observations to establish the form of the tails of the distribution. It will be recognized, therefore, that inferences concerning the tails of the distribution and based on the use of the "normal" curve must be accepted with some reserve.

An example where such care must be taken is the following. Consider the strength of cotton yarn in relation to its weaving properties. In weaving a length of cloth thousands of individual threads are placed under tension. A weak thread will cause a breakage and involve the stoppage of the loom. In deciding how frequently this is likely to occur for a given yarn it is little use basing one's predictions on the shape of the main part of the frequency distribution of yarn strength. The breakages arise from the very weak threads, which may occur no more often than, say, once in 10 000 times. The distribution is not likely to be well established in this region.

No doubt similar situations to the above occur in all industries. In such cases if one is really interested in the extremities of distributions one may be forced to adopt "factors of safety" which are very much a matter of personal choice.

Fortunately, however, for the development of the application of statistical method to engineering problems there are plenty of situations where one is concerned not with very small chances but with events which occur as often as, say, once in 20 or 10 times. Here assumptions of normality are not likely to lead to serious miscalculations. Moreover, usually one requires information about the behaviour of averages and measures of spread, and not about individuals. As the authors point out, averages of groups of observations tend to be distributed normally even when the distribution of individuals departs considerably from normality. It is not difficult to appreciate why peculiarities in the tails of the original distributions are likely to be ironed-out in the distributions of averages. The chance of obtaining a single observation out at the tail may be small—say of the order 1 in 100. If a sample of size 5 is taken it is even more unlikely that more than one such tail observation will occur. If there is only one, and this is added to the other 4 observations and an average taken, the large discrepancy due to the outstanding individual is divided by 5 and hence its importance is considerably diminished. Similar considerations apply to standard deviations, and hence it appears that statistical methods developed on the basis of the Gaussian distribution have a much wider field of application than may at first sight seem possible.

[The authors' reply to this discussion will be found on page 21.]

DISCUSSION BEFORE THE MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, 19TH FEBRUARY, 1940, ON THE ABOVE PAPER AND THE PAPER BY MR. W. T. O'DEA (SEE PAGE 22).*

Mr. F. C. Mead: During the past 20 years or so there have been many developments of statistical method, and a wealth of literature has been published dealing with the applications of statistical method in the pure sciences, notably physics and biology. In the realm of applied science, modern statistical methods have been welcomed and well used by the agriculturists, but as there are relatively few published papers dealing with the applications of statistics to engineering it appears that these extremely useful developments are comparatively unknown to the majority of engineers. The authors of these two papers draw attention to several quite simple but exceedingly useful applications of statistics to engineering practice; the more general use of these by engineers would undoubtedly result in immense saving of effort and money.

The reluctance on the part of many engineers to make use of statistical methods appears to be due to suspicion of the validity of such methods on the one hand, and fear of their complexity on the other. Much of the suspicion is, I think, due to a misunderstanding of what statistical method really is, and much of the fear of complexity is due to the statisticians, many of whom in writing or speaking about statistics pretend that it is a much more difficult subject than it really is.

It is often said that "one can prove anything by statistics." Actually, of course, the precise opposite is nearer the truth. One can prove nothing by statistics, but then statistics does not aim at proving anything. It is merely a useful tool. The lists of figures, often accompanied by graphs, showing such things as the number of deaths due to particular diseases and to road and traffic accidents, the cost of food, and so on, are often called statistics by people who should know better. They are not statistics, they are data. Numerical results of experiments, engineering or otherwise, are also data. In drawing conclusions from these data it is necessary to examine them carefully and methodically, both to assess the likelihood of possible errors and to look for systematic or chance variations and their causes. Methods have been developed which enable one to obtain measures of the likelihood of errors and the magnitude of both systematic and chance variations. It is these measures which are the results of systematic analysis of the data, which are properly termed statistics. It is the arithmetical mean, the standard deviation, the skewness and the kurtosis which are the statistics, and it is the use and interpretation of these indexes of the properties of the relevant frequency distributions which constitute statistical method. If, therefore, one uses statistical methods to test the reliability of a set of data, or to indicate by means of control charts, for example, the presence of otherwise

* At a joint meeting with the Liverpool Engineering Society.

unsuspected or unwanted influences, one knows exactly how far the data have been influenced by systematic or chance influences, and, if a manufacturing process is concerned, one is led to the source and often also to the remedy for the unsuspected or unwanted disturbance. Thus statistics provides a systematic and sure method of sorting out the multitude of separate influences which lie at the back of almost every observation we make, and which, if the existence of all of them is not realized, will lead us to quite false conclusions.

Turning now to the two papers which have been read, I am rather disappointed that neither of them refers to the use of probability graph paper, in which one of the co-ordinate scales is so constructed that a "normal error" or Gaussian frequency distribution plots as a straight line. This paper is now readily obtainable, and is exceedingly useful in determining rapidly how far a set of data approximates to a Gaussian distribution. It also enables one to read off at once from the graph, values of the arithmetic mean and the standard deviation without any elaborate calculations. Similar paper is also available for testing distributions likely to conform to Poisson's exponential summation, a slightly skew distribution of particularly common occurrence in telecommunications engineering.* Quick graphical methods have an appeal to engineers, and I firmly believe that if more publicity were given to the existence of these graphical methods of statistical analysis much of the reluctance of engineers to make use of statistical methods would be rapidly overcome.

Mr. C. D. Campbell: The underlying assumptions of the control chart in Fig. 16 of Messrs. Dudding and Jennett's paper are that there is a basic frequency distribution of readings of lamp life about the average and that, if the number of readings outside certain limits A and B increases, production is "out of control." But the frequency distribution of lamp-life readings may change from time to time, and it may be found that this is due to variables such as seasonal and cyclical changes in human conditions. For example, in winter the workers may be more tired than in summer and so do poor work, and therefore the standard deviation of lamp life may increase: or, cyclically, a boom may bring in less experienced workers, with similar effects. A recalculation of the limits in the control chart for, say, the winter might show that the new period is in control relative to itself, but is not in control relative to the summer base. There may be no way of improving the position by the application of technical engineering remedies, and the control chart would fail to lead to remedial technical action.

Mr. L. H. C. Tippett: The subject of statistics is the calculus of uncontrolled variation; it is a body of mathematical methods for describing, analysing and calculating the consequences of variation shown by any numerical data. Since the materials, products, forces and strains dealt with by engineers do vary, within limits, without control, engineers have use for statistical methods.

I have been trying to think of the kind of objection a sceptical engineer might offer to this view, and can imagine one saying "Statistical methods may be useful when you are dealing with variable materials like glass, porcelain insulators, textiles and so on, but we engineers deal with precision products; we work with great accuracy and allow little variation; we have no use for statistics." My reply to such an argument would be that, however carefully controlled the product may be, there is always some variation and often it is of importance. Whatever precision is attained there is a tendency to require greater precision, and statistics may therefore be useful in studying the small amount of uncontrolled variation that has not been eliminated.

Messrs. Dudding and Jennett advocate the control chart as a good way for engineers to approach statistics; I support this suggestion. The control chart illustrates that statistical methods are fundamentally on sound common-sense lines that commend themselves to any scientist. For example, in studying the variation in quality between batches of a product, it is natural to plot the mean quality for each batch, as is done in the control chart, and it is just as natural to ask for some criterion for deciding what degree of fluctuation between batch means signifies a real change in quality. That criterion is provided by statistical theory, and is based on the dotted horizontal lines drawn in the control charts of Messrs. Dudding and Jennett, namely the control limits. They suggest that any engineer studying the subject of statistics for the first time would do well to spend 12 months on control charts, before going on to more advanced methods. I hope the engineer will not stop at that, however, for he will find that the more advanced methods are exceedingly powerful and useful.

Mr. V. L. Farthing: From a paper which was read before the Liverpool Engineering Society 2–3 years ago I gathered the impression that if one used the right scale one could substantiate almost any conceivable argument by means of statistics. The present papers rather confirm that impression. Many engineers do not find time to bother with statistics; they tend to leave such things to statisticians, on whom they can call for information.

In another paper read before the Liverpool Engineering Society, which was published in their *Bulletin* (November, 1939), L. Schuster instanced causes of mechanical failure in service and showed that present tests did not indicate how a material would react in service under a combination of circumstances. Possibly, with the aid of statistics, a new series of tests might be evolved to ensure that all conditions of service are envisaged, and the percentage of breakdowns thus be brought to an even lower limit.

[**Mr. O'Dea's** reply to this discussion will be found on page 32.]

* For a description of the uses of probability graph paper see F. THORNDIKE: "Applications of Poisson's Probability Summation," *Bell System Technical Journal*, 1926, **5**, p. 604. For other graphical methods, particularly concerning the difficult problem of drawing reliable conclusions from very small samples, see R. D. GOODRICH: "The Straight-line Plotting of Skew Frequency Data," *Transactions of the American Society of Civil Engineers*, 1927, **91**, p. 1.

MESSRS. DUDDING AND JENNETT'S REPLY TO THE ABOVE DISCUSSIONS

Dr. B. P. Dudding and **Mr. W. J. Jennett** (*in reply*): We think it somewhat unfortunate that so much of the discussion centres around the nature of the frequency distribution curve. By concentrating on this approach to the treatment of data, workers are in danger of not obtaining that familiarity with simple statistical principles which we think so important and which may best be described as "becoming statistically minded." In particular we regret that Dr. Radley refers to "the elaborate methods of the statistician" in contrast with the simplicity he appears to associate with a study of the shape of the frequency distribution curve. We think we have fully demonstrated the essential simplicity of the methods he refers to as elaborate.

The following consideration of the data Dr. Radley presents illustrates the limitations imposed by his procedure, and suggests that his confidence in the "stability" of the data is not as well founded as his diagram would indicate. He appears to consider his sample data as sufficient data from which to draw conclusions regarding the product when the data fit closely to a standard type of frequency distribution curve. Thus the first 19 motors plot on what is judged to be an irregular line, and the data are considered to be "unstable." The addition of results for a further 17 motors yields a straight line. The data are then considered "stable," and conclusions are drawn as to the proportion of the bulk of motors having a speed less than a certain value. However, the results for the 36 motors might be fortuitously regular just as the results for the 19 motors might be fortuitously irregular. (The data for the second 17 motors would presumably be considered "unstable"—do two sets of unstable data make a set of stable data?) Conclusions as to the degree of reliability of estimates derived from sample data must be based on the variability which can be exhibited in the results for samples of the size under consideration, due to the chance of selection. In the case of the teleprinter motors, if the assumption can be made that the 36 in the sample come from a Normal distribution, then considerations of the possible sampling error in the values of the mean and standard deviation lead to the conclusion that there is a 1 in 20 chance that the proportion of motors in the bulk with speeds below 3 010 r.p.m. is as small as 1 % or as large as 6 %. Technical factors may be such that uncertainty in this estimate of the slow motors in the bulk is too large and hence a sample of 36 too small. On the other hand, the accuracy required in this estimate may be low enough for the result of tests on 19 or even fewer motors to be sufficient.

The use of probability paper, which is favoured by a number of contributors, will fail to give a true appreciation of the part that chance of selection plays in making any estimate of the nature of the bulk supply from data derived from a sample. Its use appears to be encouraged by a dislike of simple arithmetic without which the maximum technical guidance cannot be obtained from the data available.

We welcome Dr. Welch's comments on the tails of the distribution, as a careful study of his remarks will, we feel, assist in answering some of the points raised by Mr. Bruce, Mr. Fletcher and Dr. Radley. In general the statistical tool can be useful long before sufficient data are available to define accurately the tails of the distribution. The extent to which causes extraneous to the general system of chance causes are responsible for the "tail" data can be studied by the means indicated in Section 3(*c*) in our paper.

We note Mr. Stowell's reference to the early statistical work of the E.R.A. on voltage variation. Many supply engineers, in association with the British Electrical and Allied Industries Research Association, have been actively examining in some detail the applications of these principles to the problems associated with their service. The design and construction of automatic instruments to record standard deviations of supply voltage has been considered.

We think that on reflection Mr. Campbell will agree that he is directing attention to one of the applications of statistics. The identification of an "assignable" cause for some portion of the variability is part of the normal procedure in the study of any technical problem using the methods described at some length in our discussion of control charts (Section 3) and the analysis of variance (Section 5).

Mr. Bruce quotes an example which serves to illustrate one of the main principles we urge, viz. that thorough understanding of the technical problems involved and the means by which the data are obtained must be associated with a keen appreciation of statistical principles. It is only by lack of this co-ordination of technical knowledge and statistics that "one could substantiate almost any conceivable argument by means of statistics," a theorem whose truth our paper appears to have confirmed in the mind of one contributor. However, we take consolation that this contributor has over-stated his conviction in that he expresses a belief that statistics might be able to help in providing a solution to a problem with which he has been confronted.

STATISTICAL METHODS AND FACTORS OF SAFETY: AN ARGUMENT FOR THE REVISION OF EXISTING STANDARDS

By W. T. O'DEA, B.Sc.Tech., Associate Member.*

[*Paper first received 26th May, and in revised form 8th September,* 1938; *read before the* MERSEY AND NORTH WALES (LIVERPOOL) CENTRE 19*th February*, 1940. *The paper would also have been read and discussed before* THE INSTITUTION *on the 4th January*, 1940, *but the meeting was cancelled owing to the war.*]

SUMMARY

The paper demonstrates that it is impossible to discriminate, even between widely disparate batches, by the application of a constant numerical value in the form of a "factor of safety" in conjunction with a "guaranteed minimum" testing technique. It may even be that the batch with the poorer characteristics has by far the better chance of acceptance under such circumstances.

The introduction of a new set of empirical standards is recommended to replace existing "factors of safety." The new standards should be "guaranteed minima," upon which, by statistical methods of appraisement, great reliance might be placed. The statistical methods should be so devised that they substantially eliminate the necessity of empirical allowances to cover unknown degrees of variations in batch characteristics, which cannot be reliably forecast at present from results obtained from a small sample out of the batch. Thus we should eliminate the rough-and-ready technique of asking a "guaranteed minimum" strength of 10 000 lb. for line insulators while that for conductors carrying exactly the same load is only 8 000 lb. The reason for the difference is that the minimum cannot actually be guaranteed, but a greater range of variation is probable in insulators than in conductors. By statistical methods, however, the minimum can be very substantially guaranteed.

The limits of error in statistical technique are examined in some detail and the results are compared with those for present methods of appraisement, to the disadvantage of the latter. The advantages of statistical control over the processes of production and the setting of acceptance levels which may be expected with a reasonable degree of confidence to be related to the actual batch characteristics are summarized at the end of the paper.

It is also shown that present ideas of an adequate size of test sample are parsimonious to the extent of ineffectuality, and it is recommended that test samples of at least 50 units should become commonly accepted as reasonable.

LIST OF SYMBOLS

Let $x_1, x_2 \ldots x_n$ be the test results obtained from a total of n articles. Then the *mean* is given by

$$X = \frac{x_1 + x_2 + \ldots + x_n}{n}$$

The *standard deviation* is

$$s = \sqrt{\left[\frac{(X - x_1)^2 + (X - x_2)^2 + \ldots (X - x_n)^2}{n}\right]}$$

The *range* of the test results is the difference between the minimum and maximum values of x.

Also

W = estimated maximum working load.

$\frac{Z}{W}$ = "absolute minimum acceptable safety level."

X_b = mean value appertaining to the batch.

X_s = mean value appertaining to the sample drawn from a batch for test.

σ = batch standard deviation.

s = sample standard deviation.

n = number of units in the sample.

t_s and t_b = values of t (Fig. 2) corresponding respectively to the sample characteristics and the characteristics of the batch under consideration.

(1) INTRODUCTION

The usages which have become customary as the result of many years' compliance with the clauses of standard specifications should not be confused with basic facts. Factor of safety, for instance, is an instrument of which the true meaning has tended to become obscured by tradition. The development of statistical methods makes it desirable that this meaning should be examined with a view, possibly, to modifying our standards of acceptance so that the interpretation of tests shall be more in consonance with the demands of service conditions.

The statistician's philosophy was ably illustrated by Prof. Max Born's 1938 Kelvin Lecture,[1] entitled "The Statistical Laws of Nature." It is, in effect, that nothing is certain but that the chances against some happenings are so great that for all practical purposes they may be disregarded. There are, however, many cases where the chances are less overwhelming and the possibility of a certain occurrence cannot be regarded as negligible. This applies very frequently to those cases where the qualities of a large batch of units must be estimated as the result of tests on a small sample. It is almost invariably from such tests that the existence or otherwise of an adequate factor of safety must be deduced.

The chances inherent in a Central Electricity Board specification for the mechanical testing of line-insulator units have been analysed in a previous paper by the present author.[2] It was shown that although it may be hoped that the factor of safety in the case of 2 700 units comprising an accepted batch shall be not less than the 2·5 specified for each unit, there is actually an even chance, if only 18 units are type-tested, that it may be less in the case of 130 units out of the 2 700.

Under these conditions the factor of safety becomes

* The Science Museum, South Kensington.

something other than a guarantee of minimum quality. If, for instance, we regard $2 \cdot 5 \times 4\,000 = 10\,000$ lb. as the minimum level to be determined as the result of testing a sample of 18 specimens and we find that one specimen only gives 9 800 lb., can we say that the batch from which this sample was drawn is worse than one from which the minimum sample result was 10 200 lb.? The answer, if 18 is small compared with the batch size, is quite incontrovertibly "No." We should have to examine every result from each sample before we could even begin to make a tentative decision as between the two batches.

Statistical methods enable the chances inherent in sample test-results to be assessed with a degree of assurance depending on the sample size. They provide the only preponderantly scientific method of discrimination, and as such should be adopted wherever there are characteristics whose values depend on random chances; mechanical and puncture strengths may frequently be susceptible of analysis, for instance.

(2) THE STATISTICAL APPRAISEMENT OF BATCHES

Two hypothetical curves of frequency of occurrence are drawn in Fig. 1. The curves are formed by plotting against test results the number of times they occur. They are smooth; that is, they must be assumed to have been determined as the result of tests on an extremely large number of specimens with characteristics such that:—

Batch "A" has a mean strength of 13 400 lb. over an approximate range of 5 000 to 22 000 lb.
Batch "B" has a mean strength of 8 750 lb. over an approximate range of 7 000 to 10 500 lb.

The frequency curves illustrated are of what is known as the normal (Gaussian) form. By no means all cases susceptible to statistical analysis follow curves of this exact type, but the following arguments would be complicated by correction factors were any but the simplest (and quite common) shape adopted for examination.

Now let us suppose that the working load which articles comprising these two batches will have to withstand is estimated as a maximum of 3 500 lb., and a factor of safety of $2 \cdot 5$ is demanded. Then if we test the batches on the lines of a Central Electricity Board specification (i.e. 18 units out of a batch of 2 700 as a first test, and, if one unit fails, a second test, which must be 100 % successful, on a further 36 units) we should expect to make the following numbers of acceptances:—

Batch "A." Accepted 76 times out of 100.
Batch "B." Accepted once in about 250 000 times. This, statistically speaking, means certain rejection.

Suppose, however, that a factor of safety of $2 \cdot 0$ is regarded as sufficient. If this safety factor may be relied upon as being truly applicable to the batch it should represent a sufficient margin above the maximum working load to cater for unexpected overloads and for a reasonable degree of deterioration in quality with time. It is normally considered adequate, for instance, in the case of line conductors. If we adopt a factor of safety of $2 \cdot 0$ instead of $2 \cdot 5$, we accept the following:—

Batch "A." 92 % of batches.
Batch "B." Practically 100 % of batches.

These figures are very different from those given above.

But we have just stipulated that such a low factor of safety may only be contemplated, as a rule, if it is very dependable—that is, if very few units from a batch are likely to fail, in this case, below 7 000 lb. Calculations

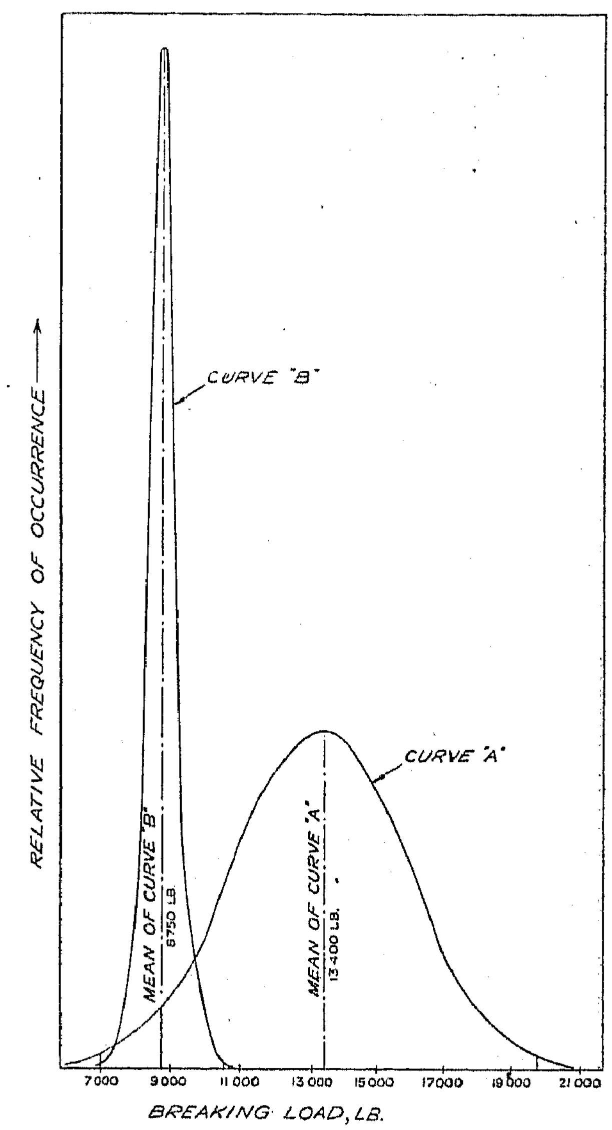


Fig. 1

which are described later in this paper show that the expectations of failures below this level are:—

Batch "A." $2 \cdot 65$ units per 1,000.
Batch "B." $0 \cdot 07$ unit per 1 000.

So that, for a maximum working load of 3 500 lb., it seems quite clear that Batch "B" is preferable to Batch "A," but if we set the factor of safety at $2 \cdot 5$ we are far more likely to accept the less suitable batch than the other. If, however, we set the factor of safety at $2 \cdot 0$ we are confronted by other dangers. Suppose, taking this lower factor of safety, that a batch is submitted for test which conforms to the shape of Curve "A," but with the mean moved to the left by an amount equivalent to 1 750 lb. 76 times out of 100 a batch of this type should be accepted, and, if it is, there is an expectation of the batch containing $2 \cdot 65$ units per 1 000

which should fail at 5 250 lb. or less, and as many as 23 units per 1 000 which should fail at 7 000 lb. or less. An accepted batch of this type might be regarded as a very dangerous state of affairs.

No matter what constant numerical value may be chosen as a factor of safety there must always be a great danger of rejecting acceptable batches and accepting poorer batches owing to the chances involved in drawing conclusions from tests on small sample numbers of units. That there may be considerable variations from the sample results has probably been appreciated for very many years, and there seems to be little doubt that many of the usual factors of safety contain a margin by which it is hoped to provide an empirical safeguard against these variations. Thus in the case of an overhead transmission line there is plainly no advantage to be gained by making the minimum mechanical strength of insulators greater than that of conductors experiencing the same maximum load, and yet the factor of safety for the former is commonly 2·5 while that for the latter is 2·0. The reason for the discrimination is that a greater range of variation may be expected in the mechanical values given by a batch of insulators, but it is only by statistical methods that a proper assessment as between the qualities of these two components of a line may be made.

A true comparison of the factors of safety of 2·0 and 2·5 in the above case is somewhat as follows: Let the estimated maximum working load be 3 500 lb. The minimum mechanical strength necessary to withstand this load must include an allowance to cater for possible error in the estimate and possible deterioration with time. Let us say it is 5 250 lb. To that figure we add an extra 1 750 lb. in the case of conductors to allow for possible variations which may not be discovered by a test on a small sample. In the case of insulators, however, we may expect the aberrations to be much greater, so we make the additional allowance 3 500 lb. That is,

$$\begin{array}{l}\text{Minimum test load} = \left\{\text{Estimated maximum working load} + \text{Empirical margin for safety}\right\} + \text{Margin for aberrations possibly undetected in test} \\ \qquad = Z + Y \quad . \quad (1)\end{array}$$

$$\text{Factor of safety} = \frac{\text{Minimum test load}}{\text{Estimated max. working load}}$$

$$= \frac{Z+Y}{W} = \frac{Z}{W} + \frac{Y}{W} = \text{Constant} + \text{Constant} \quad . \quad (2)$$

The constant Z/W applies equally to conductors and insulators in the case quoted above, and may be described as the *absolute minimum acceptable level of safety*. It is $5\,250/3\,500 = 1\cdot5$. The second constant Y/W is $1\,750/3\,500 = 0\cdot5$ in the case of conductors; and is $3\,500/3\,500 = 1\cdot0$ in the case of insulators. Therefore, taking the line as a whole, the "constant" Y/W is actually a variable. By statistical methods of test interpretation it is possible to arrive at a level for this variable without discriminating, as such, between conductors and insulators. That is, if a batch of insulators is so consistent that it approximates more closely to the quality expected from conductors, the "factor of safety" is adjusted accordingly.

An obvious case has been quoted. There is, however, an almost equally strong argument for the application of statistical methods in the attempted discrimination between batches of apparently similar articles such as several batches of insulators or several batches of conductor lengths. All decisions must depend on questions of degree of suitability; and where qualities are found to be statistically determinate statistical analysis is of great practical help.

(3) STATISTICAL ASSESSMENT OF QUALITY

Statistical methods are concerned only with "random chances." That is to say, the variants in a problem should not be due to assignable causes; or, if some of them are, the assignable cause should be eliminated as a constant, if possible, and analysis be applied to the remaining random variables. This principle was understood as long ago as 1886 when Johannes von Kries stated in his "Die Principien der Wahrscheinlichkeitsrechnung" that "The arrangement of equally likely cases must have a cogent reason and not be subject to arbitrary conditions." Assignable causes are most easily eliminated by statistical control during the processes of manufacture, and as other benefits may be derived from such control it should be adopted wherever possible. In such an event it would be necessary to insist that works test records should be available to visiting inspectors, but it would not be necessary for purchasers to station an inspector permanently at a works during the period of manufacture as, if a statistical method of assessment is to follow, it is plainly to the manufacturer's advantage to ensure that his control is adequate.

A consideration of statistical methods of control during production[3,5] is outside the scope of this paper.

(4) LIMITS OF ERROR IN STATISTICAL ANALYSIS OF TEST RESULTS

The smooth curves of Fig. 1 could only be obtained as the result of tests on vast numbers of specimens, so that all chance aberrations from normality would be smoothed out. In practice it is necessary to endeavour to estimate the type of curve to which a batch should belong by analytical inference from test results obtained from a relatively small sample. Unless the sample contains some unusually large number (of the order of, say, 1 000 units) the chances of error are not negligible. In most cases, for economic reasons the sample will consist of only 18, or at most 50, specimens. It may be shown (see Appendix II) that present ideas as to the size of a suitable sample are extremely optimistic, and at least 30 specimens, and preferably 50, should always be tested if we are to draw reasonably definite conclusions from the results. The increase from 18 to 50 sample units in a batch of 2 700, for instance, increases the cost by something less than 2 %, and very substantial advantages may be gained thereby.

Suppose that the present set of empirical constants known as "factors of safety" were to be replaced by a technique whereby "statistical certificates of quality"

might be issued in their stead. Then it would first be necessary to arrive at a new set of empirical standards to represent the absolute minimum acceptable level of safety expressed by the term Z/W in equation (2) above. These levels would have to be arrived at by making the following allowances over and above the estimated maximum working load: (*a*) An allowance as a safety margin above the estimated normal maximum to provide for such factors as the human element, highly exceptional of a factor of safety without the disadvantage of not being able to allow for the possibility that we have been so lucky or unlucky as to draw or not to draw a representative sample for test. By statistical analysis we may be substantially assured that we can guarantee that an accepted batch very probably does not depart very much from the level of the desired factor of safety. That being the case, we can afford to make what appears superficially to be a reduction in the standards to be applied.

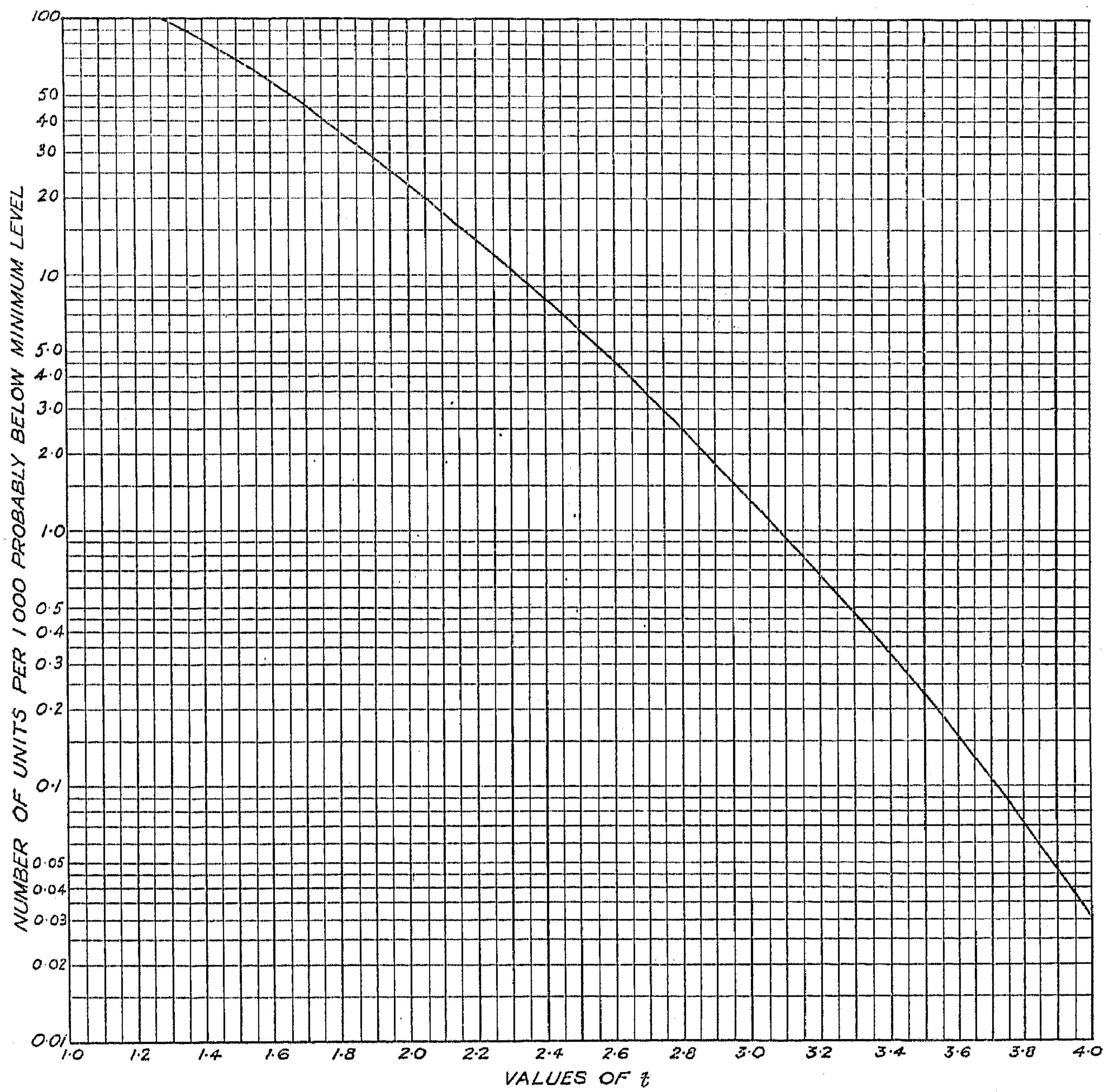


Fig. 2

weather conditions, or other loadings. (*b*) An allowance for possible deterioration in quality with time, determined where possible as the result of experimental observation. (*c*) An allowance in some cases to cater for the effects of coincident loadings in service where tests are taken with these loadings reviewed separately.

The final result should be a figure somewhat less than the maximum estimated working load multiplied by the present-day factor of safety, as it should include no allowance for aberrations in the batch which have not necessarily been detected by the type tests (that is, the term $\frac{Y}{W}$). Now if it were possible really to guarantee this " absolute minimum " we should retain the advantages In actual practice the apparent reduction in the acceptance level, as will be shown below, is a device whereby we may be enabled to accept a batch such as that represented by Curve " B " (Fig. 1) which would not pass the present-day factor-of-safety levels, but is in fact preferable to a batch such as that represented by Curve " A " (Fig. 1) which should at present be accepted 76 times out of 100. At the same time the new acceptance levels may be so defined that there is practically no fear of also allowing a number of batches of less desirability to be accepted; in fact, it may be made harder for batches to Curve " A " to pass the tests.

Two important and to some extent interdependent indications of quality may be obtained for any batch of

articles susceptible of statistical analysis. They are the *mean* and the *standard deviation* (see List of Symbols, page 22). It so happens, taking the normal form of curve of frequency distribution, that we may define the percentage of observations which may be expected to fall below or above levels represented by (The mean — t times the standard deviation), for any values of t. The curve of Fig. 2 shows the number of specimens per 1 000 in a batch which may be expected to be of lower quality than that represented by

$$\text{Mean} - (t \times \text{standard deviation})$$

Provided that we know the mean and the standard deviation applicable to a batch, we may estimate with confidence the chances of encountering numbers of specimens of less than some definite standard of quality. In order to obtain these figures, however, we should have to test every unit in the batch, and there would then be no need for estimation. In practice we can only test a small sample from the batch, and from that we can obtain the figures for mean and standard deviation applicable to the sample. We are forced, in appraising the probable quality of the batch, to take these sample standards as though they were actually batch values. This introduces a probability of error, but again the chances may be estimated.

Suppose, from the results of tests on a small sample of n units drawn from a batch, we arrive at a mean sample value X_s and a sample standard deviation s. Suppose that the values of these characteristics, were we able to test every unit in the batch instead of a small sample, should be X_b and σ. Then it is possible to show, having obtained sample values, that the corresponding batch values should be expected to lie within the limits defined in Table 1 and Appendix III.

Similar expressions to those given in Table 1 may be derived for any other degrees of expectation, the appropriate numerical constant being obtained by reference to Table II of Karl Pearson's "Tables for Statisticians and Biometricians."[4] They are the values of t indicated in Fig. 2. Thus, for an expectation of 999 times out of 1 000 we should take the t corresponding to 1·0 in Fig. 2, i.e. the constant in the expressions for the probable limits becomes 3·09. In 999 cases out of 1 000 we should therefore expect the batch mean to be not less than

$$X_s - \frac{3 \cdot 09}{\sqrt{(n-3)}} s, \text{ etc.}$$

The significance of the number in the test sample (n) becomes immediately apparent. It is obvious that the greater the number of sample units drawn from a batch, the less should be the probable variation of the batch mean from the sample mean, and of the batch standard-deviation from the sample standard-deviation. If n is 50, for instance, we may expect in only 1 case in 100 that the batch mean should be less than (Sample mean — 0·34 × standard deviation); the chances are also 100 to 1 against the batch standard-deviation being greater than 1·3 times the sample standard-deviation. If, however, the sample contains only 20 units the factor 0·34 mentioned above becomes 0·56 and the factor 1·3 becomes 1·6. If the sample is only 10 units the factors become 0·87 and 2·63 respectively, and so on (with the proviso that the proposition becomes increasingly vague as n approaches 3). If the standard deviation is at all comparable with the mean it will be seen that tests on too small a sample may be very misleading.

Table 1

Expectation for each limit given	Mean, X_b		Standard deviation, σ	
	Not less than	Not more than	Not more than	Not less than
95 times out of 100	$X_s - \frac{1 \cdot 645}{\sqrt{(n-3)}} s$	$X_s + \frac{1 \cdot 645}{\sqrt{(n-3)}} s$	$\frac{1}{1 - \frac{1 \cdot 645}{\sqrt{(2n)}}} s$	$\frac{1}{1 + \frac{1 \cdot 645}{\sqrt{(2n)}}} s$
99 times out of 100	$X_s - \frac{2 \cdot 326}{\sqrt{(n-3)}} s$	$X_s + \frac{2 \cdot 326}{\sqrt{(n-3)}} s$	$\frac{1}{1 - \frac{2 \cdot 326}{\sqrt{(2n)}}} s$	$\frac{1}{1 + \frac{2 \cdot 326}{\sqrt{(2n)}}} s$

It may be stated categorically that present-day conceptions of adequate sample sizes are pusillanimous to the point of absurdity in many cases. The cost of increasing the numbers in a test sample has not been scientifically weighed against the value of reducing the probable range of variation of batch characteristics from those of the sample (see Appendix II). A minimum sample size of 50 units is desirable in a great many cases where any number from 3 to 18 is at present commonly regarded as sufficient. A numerical example may be taken to illustrate the range of variation which may be expected even when the sample size is as high as 50 units.

Suppose that from tests on 50 units we obtain a sample mean of 8 750 lb. and a sample standard-deviation of 460 lb. when testing for mechanical strength. Then we should expect, if the batch figures could be taken as being the same as those for the sample, that the batch should

conform to Curve "B". (Fig. 1). Unfortunately this is unlikely to be so, but we know from Table 1 that the expectation, in 99 cases out of 100, is that the actual batch mean should not be less than

$$8\ 750 - (0\cdot 34 \times 460) = 8\ 594 \text{ lb.}$$

Nor, in 99 cases out of 100, should it be greater than

$$8\ 750 + (0\cdot 34 \times 460) = 8\ 906 \text{ lb.}$$

(In 98 cases out of 100 it should lie between these limits.)

Similarly, in 98 cases out of 100 the batch standard-deviation should lie between $1\cdot 3 \times 460$ lb. and $0\cdot 81 \times 460$ lb.

Let us now take another set of sample results which should indicate, were there not a probability of aberrations from the batch figures in the sample results, that the batch conformed to Curve "A" (Fig. 1). Such results are a sample mean of 13 400 lb. and a sample standard-deviation of 2 300 lb. In 98 cases out of 100 the batch means corresponding thereto should lie between 12 620 lb. and 14 180 lb.; and in 98 cases out of 100 the batch standard-deviations should lie between 3 000 lb. and 1 880 lb.

The chances of discriminating between Batch "A" and Batch "B" (Fig. 1) have already been examined, in Section (2), and have been found to be exceedingly poor (in view of the disparity between the batches) by "factor of safety" standards. Batch "B" corresponded to an expectation of $0\cdot 072$ unit per 1 000 failing below 7 000 lb. This expectation is calculated as follows:—

$$\text{Mean} = 8\ 750 \text{ lb.}; \text{ standard deviation} = 460 \text{ lb.}$$

$$\frac{\text{Mean} - 7\ 000}{\text{Standard deviation}} = 3\cdot 8 = t \quad \text{(Fig. 2)}$$

Suppose that we consider such a small expectation of highly defective units to be acceptably low. Batch "B," in other words, is acceptable, but we can only guess whether the batch is as good as this from the results of tests on a sample of 50 units. Sometimes the sample results will be better than the batch characteristics, sometimes worse. If, therefore, we were to put the sample acceptance level at the desired batch level we might expect to reject 50 % of batches which actually conform to the acceptable characteristics represented by Curve "B" (Fig. 1). It seems, then, that we must forgo counsels of perfection and content ourselves with a compromise to allow for possible aberrations in the sample results. Let us now examine what should be expected to happen if we put the sample acceptance level somewhat higher—for example, at the expectation of $0\cdot 75$ unit per 1 000 failing below 7 000 lb.—provided the sample results were the same as the batch figures.

It will be seen as a corollary that we should then accept 50 % of submitted batches in which the actual level of defectives was $0\cdot 75$ per 1 000 failing at less than 7 000 lb. We should at the same time accept much more than 50 % of batches in which the actual level was as low as $0\cdot 072$ per 1 000 below 7 000 lb. In order to obtain a quantitative idea of what this means the following process may be applied to various levels of disparity between sample and batch levels.

Obtaining values of t (Fig. 2), we have

$$t_b = \frac{X_b - 7\ 000}{\sigma}; \quad t_s = \frac{X_s - 7\ 000}{s}$$

$$\frac{t_b}{t_s} = \frac{s}{\sigma}\cdot\frac{(X_b - 7\ 000)}{(X_s - 7\ 000)} \quad . \quad . \quad . \quad . \quad (3)$$

but, from Table 1,

$$X_b = X_s \pm \frac{C}{\sqrt{(n-3)}}s$$

so that

$$\frac{t_b}{t_s} = \frac{s}{\sigma}\,\frac{\left(X_s - 7\ 000 \pm \dfrac{C}{\sqrt{(n-3)}}s\right)}{(X_s - 7\ 000)}$$

$$= \frac{s}{\sigma}\left[1 \pm \left(\frac{C}{\sqrt{(n-3)}}\cdot\frac{1}{\dfrac{X_s - 7\ 000}{s}}\right)\right]$$

$$= \frac{s}{\sigma}\left[1 \pm \left(\frac{C}{\sqrt{(n-3)}}\cdot\frac{1}{t_s}\right)\right] \quad . \quad . \quad (4)$$

Suppose the sample acceptance level is put at $0\cdot 75$ unit per 1 000 defective, and we wish to know the probability of accepting batches in which the actual level of defectives differs from this. For an expectation of 9 times out of 10, C for variations in the means in the above expression will be $1\cdot 645$. [For 98 times out of 100 it would be $2\cdot 326$, etc. (see Table 1)]. Suppose that the number in the sample (n) is 50; then t_s, for $0\cdot 75$ unit per 1 000 defective, is $3\cdot 175$ (from Fig. 2). t_b, for various batch levels, can also be determined from Fig. 2.

$$\frac{t_b}{t_s} = \frac{s}{\sigma}\left(1 \pm \frac{1\cdot 645}{6\cdot 87}\cdot\frac{1}{3\cdot 175}\right) \text{ 9 times out of 10}$$

But,

$$\sigma = \frac{1}{1 + \dfrac{k}{\sqrt{(2n)}}}s \text{ from Table 1}$$

where k is a constant of either positive or negative sign which indicates the probability of the event. This gives

$$1 + \frac{k}{10} = \frac{t_b/t_s}{1 \pm 0\cdot 075} \quad . \quad . \quad . \quad . \quad (5)$$

Values within which k may be expected to lie 9 times out of 10 may be calculated from the above expression at various levels for t_b/t_s.

Table 2 has been calculated at various levels, the figures in the last column being obtained by putting $k = x$ in Table 2 of Pearson's tables.[4]

The values given in the last column are plotted, with comments, in Fig. 3.

The significance of Table 2 is as follows: A batch of units put up for test may contain a total proportion

of defective units as indicated in column 1. A sample is chosen from the batch for actual test, and the sample characteristics may vary by quite an appreciable amount from those of the batch from which it was drawn. The acceptance level is that the sample shall indicate not more than 0·75 unit per 1 000 defective. Depending on how far the sample means and standard deviations, considered together, vary from those of the batch, so will the chance of acceptance vary. Nine times out of 10, however, the percentage probability that the batch will be accepted should lie within the limits given in the last column.

Table 2

True batch level (defective units per 1 000)	t_b	$\frac{t_b}{3\cdot175}$	Range of k	Limits within which, 9 times out of 10, lies the expectation of accepting the batch sampled (per cent)
0·1	3·72	1·17	0·884 to 2·648	81 to 99·6
0·25	3·48	1·097	0·205 to 1·86	58 to 97
0·4	3·35	1·06	– 0·14 to 1·46	44 to 93
0·5	3·29	1·036	– 0·363 to 1·20	36 to 88
0·6	3·24	1·02	– 0·52 to 1·02	30 to 85
0·75	3·175	1·00	– 0·70 to 0·81	24 to 79
1·0	3·09	0·97	– 0·98 to 0·486	16 to 68
1·5	2·97	0·935	– 1·3 to 0·1	10 to 54
2·0	2·88	0·906	– 1·57 to – 0·2	6 to 42
3·0	2·75	0·86	– 2·0 to – 0·7	2·3 to 24
5·0	2·58	0·81	– 2·47 to – 1·25	0·7 to 10·6
7·0	2·46	0·775	– 2·79 to – 1·62	0·3 to 5·3

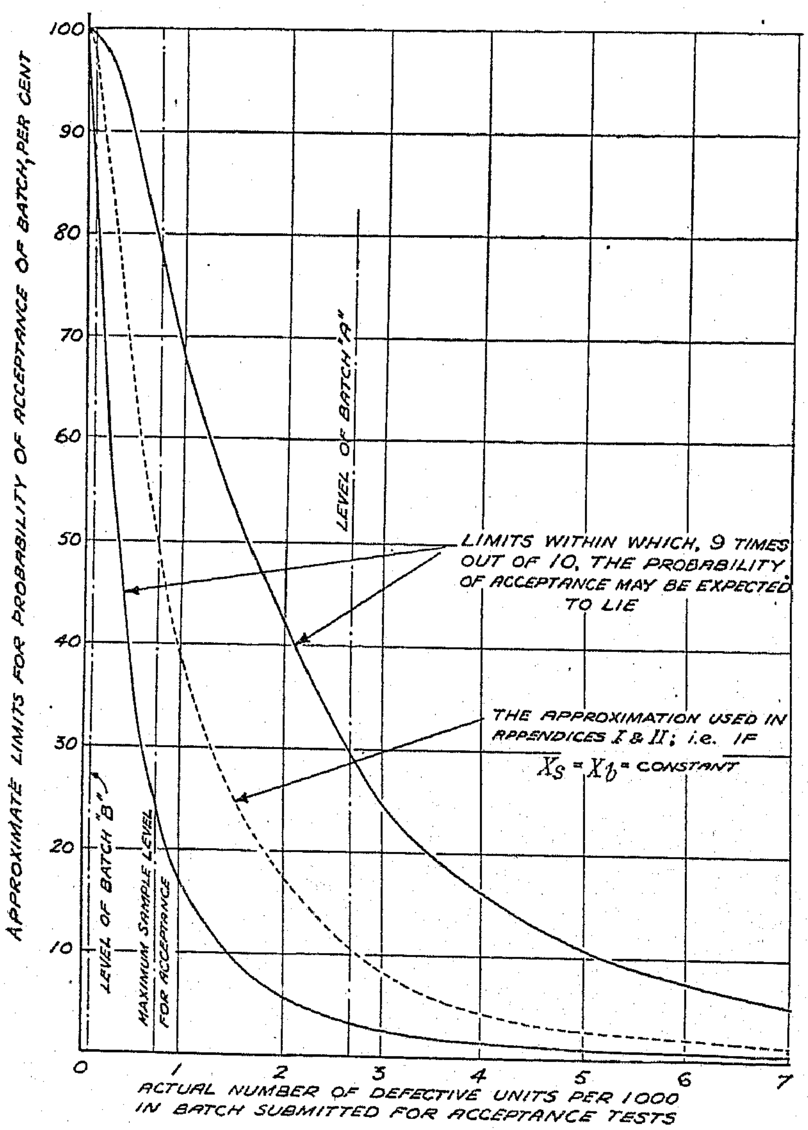


Fig. 3
Sample contains 50 units.

Reverting to the batches labelled " A " and " B " in which the levels of defectives were 2·65 and 0·072 per 1 000 respectively, the following probabilities of acceptance may be expected 9 times out of 10: Batch " A," between 3 % and 30 %; Batch " B," between 90 % and 99·8 %. The probability of accepting a batch corresponding to Curve " A " shifted 1 750 lb. to the left (23 per 1 000 defective) is practically zero. Therefore the statistical method of appraisement described above is far better than the " guaranteed minimum " test.

Calling the batch in which 23 units per 1 000 are defective Batch " C," the position may be summarized as shown in Table 3.

Table 3

	Probability of acceptance (per cent)		
	Statistical test*	Safety factor 2·0	2·5
Batch " A "	3 to 30	92	76
Batch " B "	90 to 99·8	Practically 100	Practically nil
Batch " C "	Practically nil	76	13

* 9 times out of 10 between these limits.

The value of the statistical test may be gauged from the fact that Batch " B " is clearly the most desirable for service conditions, but it is undesirable to accept

Batch "A" and particularly undesirable to accept Batch "C."

The case quoted is hypothetical. It will be appreciated that similar calculations may be made to cover any particular set of practical conditions and that as long as the qualities under consideration are statistically determinate (that is, varying through random chances) the application of the methods of statistical analysis to an interpretation of sample test-results is bound to be of advantage, in greater or less degree, compared with an attempt to determine batch characteristics by sample "guaranteed minima."

(5) THE ADVANTAGES OF STATISTICAL METHODS

The arguments in favour of the use of statistical methods will now be summarized.

(*a*) The range of possibilities which must be considered when applying factors of safety based on the present conceptions of the term is so wide that conclusions drawn from tests on a small sample may be (i) so far from the truth as to be valueless; or (ii) substantially true, but not indicative of the suitability of the batch for service. There is no means of gauging the chances of applicability of either of these conditions.

(*b*) The range of possibilities which must be considered when applying a statistical method of interpretation to test results is narrower and may also be defined. It is indeterminate only in so far as the limits of reasonable certainty must be related to the economic factor.

(*c*) Statistical methods may be used to define one of the variable components of a "factor of safety." We may, with reasonable certainty, be satisfied that what might be called "pre-service variables" are very substantially eliminated by statistical analysis. We are then left with the necessity of arriving at an empirical acceptance level involving only one set of variables instead of two; that is, an allowance above the estimated maximum working load to cater for the possibility of very abnormal service conditions or for deterioration.

(*d*) The elimination of "pre-service variables" should make it easier to correlate, on a satisfactory basis, the qualities of the component parts of an entity. That is, in an entity such as an overhead transmission line, the basic strengths of conductors and insulators should more easily be matched.

(*e*) The encouragement of consistency in quality by statistical analysis should promote, incidentally, consistency in behaviour in service. This, in turn, should make it easier to arrive at satisfactory empirical constants for the term Z/W in equation (2).

(*f*) The setting of statistical acceptance levels, as mentioned in Section (3), involves the application of statistical control to production. This in itself should do much to further the cause of consistency.

It is not easy to produce any substantial objections to the introduction of statistical methods in place of the present-day factor of safety and guaranteed minimum, but the following points may be mentioned.

(*g*) A new set of empirical minimum limits (Z/W) would have to be determined, and this should take time and might also involve a few expensive misjudgments. On the other hand, our present empirical standards are so uncertain in their application that it is difficult to imagine that the amount of trouble would be even temporarily increased.

(*h*) Statistical control of production might give rise to certain temporary problems in works organization. It might also be applied in some cases where the product was not really susceptible to such control; but these cases should become self-evident before long.

(*j*) The duties of an inspector would become a little more involved.

(*k*) Larger samples would be required, and this might appear superficially to be an economic disadvantage. The actual position is that present-day conceptions of suitable sample sizes are almost ludicrously inadequate, and revision is long overdue if we are to reap advantages which should more than repay the slightly increased cost of larger samples.

(*m*) It should be appreciated that where a rating of, say, 50 000 lb. per sq. in. might be given to a product under present conditions, if a statistical technique for batch acceptances was introduced this rating might have to be reduced to, say, 40 000 lb. per sq. in. At the same time, as the factor Z/W should be less than the present "factor of safety," the employment of the lower rating in engineering calculations should be economically sound in conjunction with the lower factor. In fact, the increased confidence to be placed in batches accepted as the result of statistical analysis of test results should lead, in time, to the establishment of more economical relationships between ratings and service conditions.

REFERENCES

(1) M. Born: "Statistical Laws of Nature" (29th Kelvin Lecture), *Journal I.E.E.*, 1938, **83**, p. 802.

(2) W. T. O'Dea: "A Statistical Examination of Specifications for the Mechanical Testing of Line Insulators," *ibid.*, 1938, **83**, p. 333.

(3) E. S. Pearson: "Statistical Methods in Standardization" (B.S.S. No. 600—1935).

(4) Karl Pearson: "Tables for Statisticians and Biometricians," Part 1 (Cambridge University Press).

(5) The following papers by B. P. Dudding and I. M. Baker deal with problems of statistical control of production:—

"The Application of Statistical Methods to the Quality Control of Manufactured Products," *Journal of the Society of Glass Technology*, September, 1933.

"The Application of Statistical Methods to the Planning of Routine Test Procedure," *ibid.*, March, 1934.

(6) A list of many books, papers, etc., on statistical methods applied to engineering subjects will be found in Appendix VIII of Reference (3).

(7) For an introduction to the theory of statistics (as

distinct from the application of statistical methods), see

(i) ARNE FISHER: "The Mathematical Theory of Probabilities" (Macmillan, New York, 1915).

(ii) G. UDNY YULE and M. G. KENDALL: "An Introduction to the Theory of Statistics" (Charles Griffin, 1937).

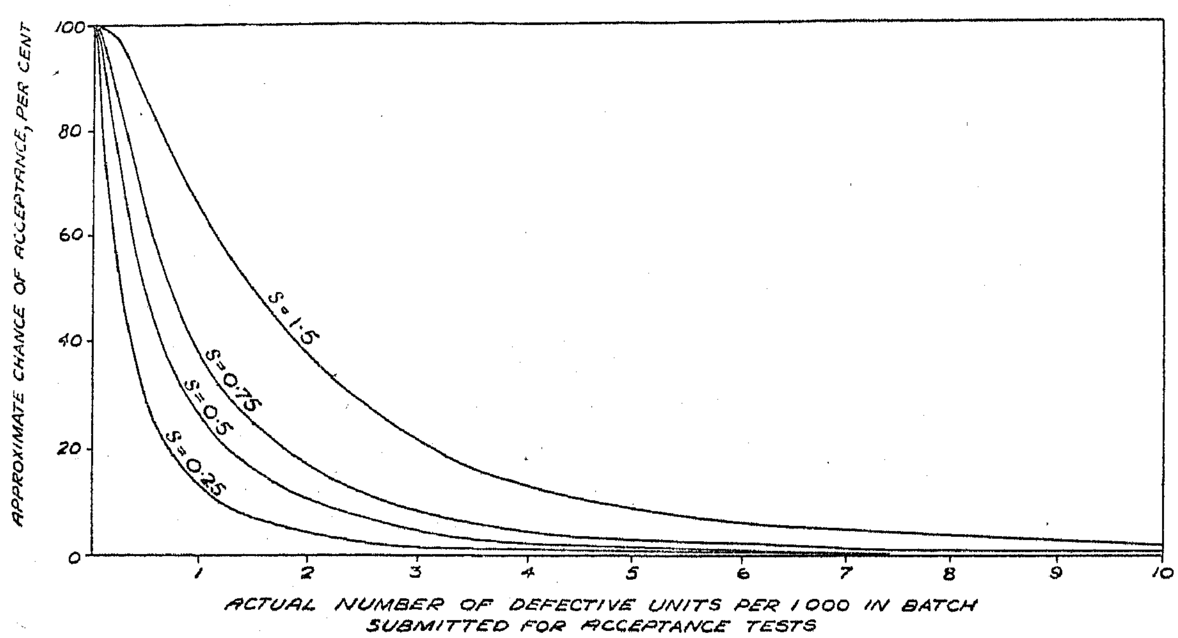


Fig. 4

Sample contains 50 units. Curves show ranges of probable batch acceptances corresponding to various sample acceptance levels (s per 1 000 defective).

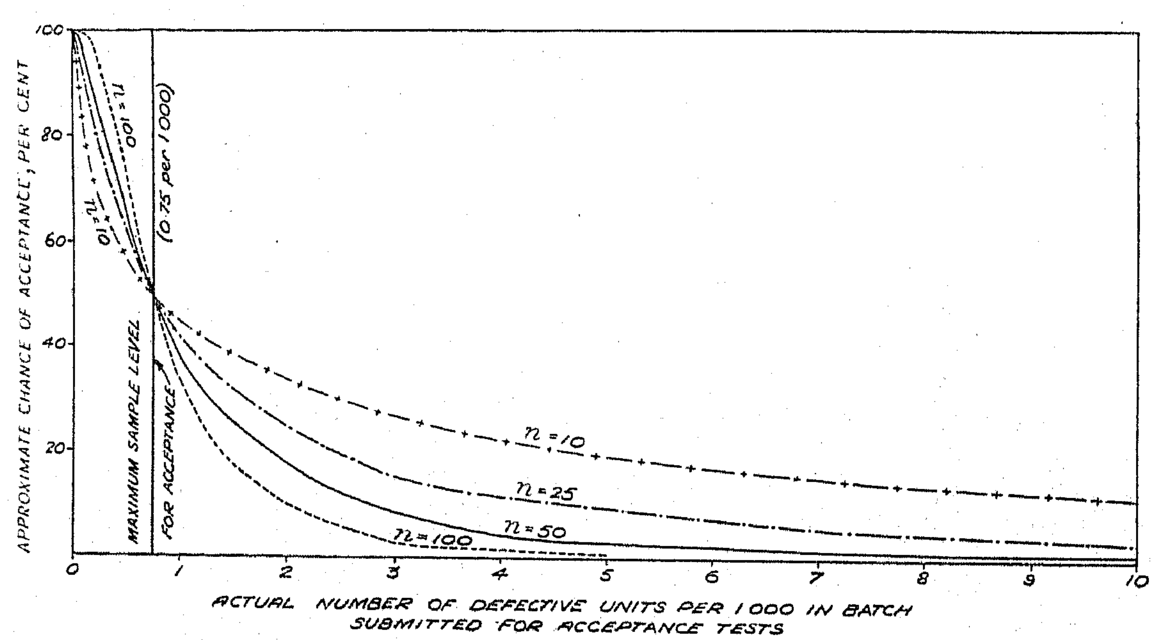


Fig. 5.—Effect of varying sample size on probability of accepting worse or rejecting better batches than those desired (number in sample = n).

APPENDICES

The curves described in Appendix 1 and Appendix 2 have been constructed on the assumption that only the sample standard-deviations vary and that the sample means remain constant at the level of the batch means. This is a fairly coarse approximation, but is justified on the grounds of simplicity as it is easier to compare families of curves than a succession of boundaries. The relative significance of the curves of Figs. 4 and 5 may be accepted with confidence, but a certain amount of caution is necessary in interpreting the numerical values which are read off.

Appendix 1. The Effect of Altering the Sample Acceptance Level

It is obvious that by altering the constant by which t_b is divided in column 3 of Table 2 it is possible to produce curves showing the effects on Fig. 3 of setting values other than 0·75 per 1 000 defective as the maximum sample limit. This has been done in Fig. 4 (but assuming, for simplicity, that $X_s = X_b =$ constant), from which it will be seen that as we become more lenient in the sample acceptance level we accept a greater proportion of worthy batches but at the same time accept a higher proportion of highly unworthy batches. The sample level finally adopted should take cognizance of these factors.

Appendix 2. The Effect of Altering the Number in the Sample

Referring to equation (3) and Table 1, we have

$$\frac{t_b}{t_s} = \frac{s}{\sigma} = 1 \pm \frac{C}{\sqrt{(2n)}}, \text{ if it is assumed that } X_s = X_b.$$

Thus

$$C = \pm\sqrt{(2n)}\left(\frac{t_b}{t_s} - 1\right) \quad . \quad . \quad . \quad (6)$$

For an acceptance level of 0·75 unit per 1 000 defective, the term t_b/t_s has been tabulated in Table 2. Here n is the number of units in the test sample. Therefore we may calculate values of C in expression (6) corresponding to various sizes of test sample. The results are shown in Fig. 5, from which the importance of including an adequate number of units in the test sample may be deduced without the necessity of explanation.

Appendix 3. Reduction in Limits of Accuracy for Low Values of n

The term $\sqrt{(n - 3)}$ in Table 1 is determined from a consideration of what are known as " degrees of freedom," and these in their turn imply that n is large compared with 3. It is obvious, for instance, that there cannot be an infinite possible variation in the sample mean relative to the batch mean when $n = 3$.

When $n = 30$ to 50 the foregoing calculations are precise enough for all practical purposes. The curve for $n = 10$ in Fig. 5 is approaching the region where results must be regarded as somewhat vague indications of what may be expected to happen. The limits of probable variation from this curve, calculated in the same way as for Fig. 3, should be rather wide. If, however, the curves of Fig. 5 are compared irrespective of the limits appertaining to each, the comparison detracts from the argument in favour of the larger samples. In practice, therefore, the case for the larger sample is stronger than that depicted in Fig. 5.

Fig. 5 shows clearly that when $n = 10$ the probability of acceptance or rejection is becoming but vaguely related to the specified standard. It should be understood that this vagueness is even more marked in the case of " guaranteed minimum " testing.

WRITTEN CONTRIBUTION TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Dr. B. P. Dudding and **Mr. W. J. Jennett:** There are two important features of the paper that require comment.

First, a word of caution should be sounded with regard to the objective of the paper—the substitution of statistical measures for empirical factors of safety. This is a laudable aim, but the author is suggesting the use of a somewhat treacherous path when he directs the engineer to use statistical measures associated with the extreme tail of the normal distribution. The questions which arise in this connection are briefly referred to in our paper.* Such use of statistical measures can only be justified when adequate data exist which provide evidence that the observations in the tail of the distribution belong to the general distribution and have not been influenced by sources of variation which are extraneous to the general system of chance causes which give rise to the family of observations from which the statistical measures are calculated.

Second, if the assumption of normality be accepted the author does not solve the statistical problem he sets himself. This problem is of the type discussed on page 8 of our paper and concerns the study of the statistical variation of the proportion of " defectives " in samples by consideration of the mean values and standard deviations of the samples. The treatment of such a problem has been given by Jennett and Welch.†

Using the author's notation,‡ the particular question from page 27 of the paper would appear in its simplest form to be: Given various values of $t_b = (X_b - 7\,000)/\sigma$ for the batch, what are the probabilities of the values for samples of 50 of $t_s = (X_s - 7\,000)/s$ exceeding 3·175?

X_s and s vary independently and simultaneously, whereas the author considers their variations separately. For any one value of t_b the probability of t_s exceeding a limit value is a simple single proportion and not the compound combination given in Table 2. The probabilities shown in Table A (a revision of Table 2) have been calculated from the formulae given by Jennett and Welch.

Table A

True batch level (defective units per 1 000)	t_b	k	Expectation of accepting the batch sampled
			per cent
0·1	3·72	1·56	94
0·25	3·48	0·87	81
0·4	3·35	0·50	69
0·5	3·29	0·33	63
0·6	3·24	0·18	57
0·75	3·175	0	50
1·0	3·09	− 0·24	41
1·5	2·97	− 0·59	28
2·0	2·88	− 0·84	20
3·0	2·75	− 1·21	11
5·0	2·58	− 1·70	4
7·0	2·46	− 2·04	2

The error in the author's treatment of the above problem is emphasized in his Appendices, where he wrongly neglects altogether the variation of X_s, the mean value of the sample.

* See page 1.
† Supplement to *Journal of the Royal Statistical Society*, 1939, 6, p. 80.
‡ It should be noted that t_b and t_s correspond to U and u in our paper.

THE AUTHOR'S REPLY TO THE ABOVE WRITTEN COMMUNICATION AND TO THE DISCUSSION BEFORE THE MERSEY AND NORTH WALES (LIVERPOOL) CENTRE (SEE PAGE 19).

Mr. W. T. O'Dea (*in reply*): Dr. Dudding and Mr. Jennett seem to have overlooked the fact that the term Z in my paper remains empirical but that it is suggested that Y, instead of remaining an empirical constant, might more scientifically be assessed as a statistical variable. They also appear to over-emphasize those mathematically pure aspects of statistics that have so often frightened engineers away from an applied mathematical tool of great value.

The dangers of making deductions from extreme tails of distributions are obvious; but so are the dangers of making deductions from factors of safety as illustrated in this and a previous paper.* The former dangers may well be the lesser.

My paper was written early in 1938. Since then Messrs. Jennett and Welch have gone further into the variations of X_s and s, but it is not correct to say that these were considered independently in my paper. The values in Table 2 and Table A are in accord. As far as the curves in the appendices are concerned, it is clearly stated that variations in X_s have been neglected for the sake of simplicity and a warning is given against reading off exact numerical values. For the purpose of comparison and illustration the approximation is well within the philosophical limits required.

Mr. Tippett rightly draws attention to the common fallacy that engineering is, or should be, concerned with precision products. In very many cases the precision applies only to dimensions, and then only if every article is gauged. The factor of safety is a simple " go and no-go " gauge that is applied to the qualities of only very few articles from a batch. Statistical gauging, though not perfect, may often be preferable, as illustrated by the examples in the paper (which have been confirmed within my own experience).

In reply to Mr. Farthing it may be stated that, for engineering problems, the " statistician " must necessarily be first an engineer in order that he may understand the philosophical implications of his mathematical analyses. Unfortunately, many engineers have no time for philosophy, which may be, paradoxically, why they have no time.

* See Reference (2).

HIGH-VOLTAGE DISTRIBUTION IN RURAL AREAS

By K. L. MAY, Associate Member.*

(*Paper first received* 31*st May, and in revised form* 25*th September,* 1939; *read before the* Northern Ireland Sub-Centre 16*th January,* 1940. *The paper would also have been read and discussed before the* Transmission Section *on the* 10*th January, but the meeting was cancelled owing to the war.*)

SUMMARY

The intention of this paper is to review in general form the possibilities of high-voltage distribution in rural areas, and details are given of the development of overhead line design which incorporates both high-voltage and low-voltage lines on the same pole.

A brief examination is made of the use of steel conductors, and comparisons are drawn with copper conductors.

Graphs and tables which have practical value to both distribution and constructional engineers are included in the paper, as also are sketches showing design for light-construction h.v. and combined construction h.v./l.v. lines.

The advantages offered by, and the steps it is necessary to take in order to obtain the full benefit of, the modifications of the Overhead Line Regulations covered by the Electricity Commissioners' circular letter M.2854 dated 24/9/37 and the Post Office Regulations Form E-in-C. 229 (November, 1938) are explored in detail.

In preparing the paper the author has endeavoured to concentrate upon essential factors in the design, construction and economics of h.v. distribution lines, giving a minimum of attention to purely theoretical points.

INTRODUCTION

In the development of rural electrification distribution engineers are repeatedly faced with the difficulty of preparing economic schemes for isolated areas, villages, or farms. The added interests of all the parties concerned, which are used to urge development in thin areas, present a serious problem.

A canvass or survey of these areas and villages will not always show an adequate estimated revenue return sufficient to justify the capital expenditure necessary for its development. The inevitable result is a general cutting down in the specification of the h.v. and l.v. distribution networks in order to reduce costs. Consequently, during the past few years, we find medium- and high-tensile steel conductors coming rapidly into prominence for the h.v. overhead line section of rural schemes.

It is in the natural order of things that the "thinner" areas should be the last to be developed, and we have now entered the period during which the bulk of new h.v. overhead mileage is being constructed for servicing these thinner areas. The impression that steel conductors of about 7/14 or 7/12 S.W.G. provide the medium for building the cheapest possible h.v. overhead lines had gained considerable ground, although the recent concession made by the Electricity Commissioners (circular letter M.2854 dated 24/9/37) regarding ice loadings to be allowed for, for small conductors, has given a check to the use of steel.

Steel conductors have one salient feature, namely low initial cost, which has led to their present frequent use. Disadvantages, however, are many, amongst which may be mentioned small carrying capacity, low margin for development of load, comparatively short life (particularly in industrial areas and sea coast areas), high physical stresses put upon terminal and angle poles, and the necessity for straight lines if low costs are to be realized. It follows that if an alternative can be found which will eliminate these disadvantages without increasing capital outlay, the supply authority must benefit very considerably thereby.

A description is given in this paper of types of construction which seem to meet the specification for the ideal rural scheme, and an attempt is also made to show that the use of copper conductors is the soundest policy.

(1) THE IDEAL RURAL LINE

The requisite qualifications for the ideal rural line can be briefly given as:—

(*a*) Flexibility as regards route.
(*b*) Adaptability for isolated supplies *en route.*
(*c*) Margin for development of load.
(*d*) Low initial cost.
(*e*) Reliability and low maintenance cost.
(*f*) Simplicity of construction with a minimum of standard parts.
(*g*) Inconspicuousness.

(2) DESIGN

Fig. 1 shows the arrangement for 11-kV straight-line, section, and medium-angle poles. 1 000-lb. swan-neck brackets are used for all straight-line poles and also for angles where the line deflection does not exceed the angles given below:—

0·04 sq. in. copper	..	..	19°
0·025 sq. in. copper	..	..	31°

For angles greater than the above the same construction may be followed, with the exception that 3 000-lb. swan-necks should be fitted, but care should be taken to ensure that the horizontal component of the spacing is not seriously reduced. A line deflection of about 60° would be a reasonable maximum to adopt.

3 000-lb. swan-necks are recommended for all section points.

Figs. 2 and 3 show the arrangement for heavy angle and terminal poles which incorporates 3 000-lb. swan-necks or one unit disc insulation. With the swan-neck arrangement this allows the following maximum angles to be negotiated without recourse to terminating on each side of a pole:—

* Edmundsons' Electricity Corporation, Ltd.

0·04 sq. in. copper	.. ..	60°
0·025 sq. in. copper	.. ..	105°

As will be seen from Fig. 3, the usual type of heavy

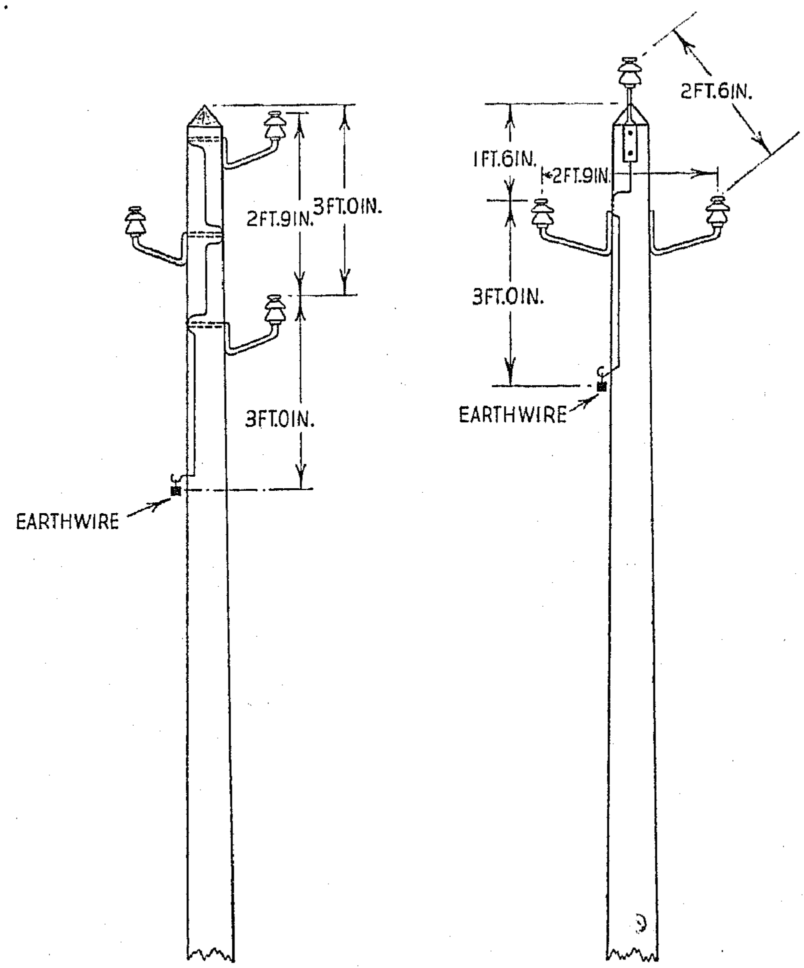


Fig. 1.—Arrangement for straight-line, section, and medium-angle poles.

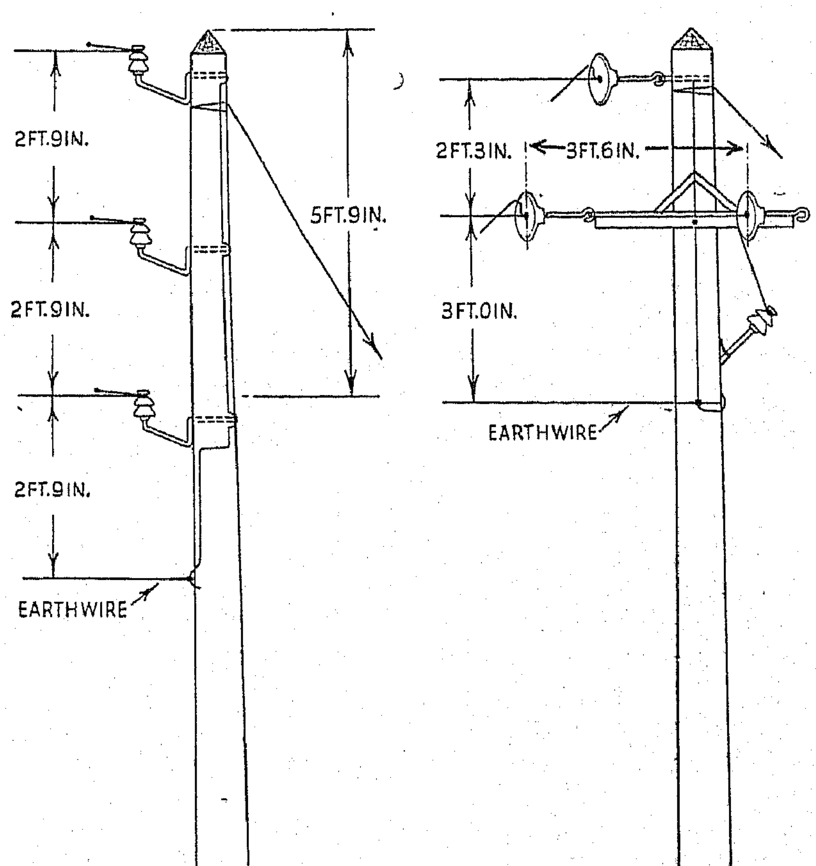


Fig. 2.—Arrangement for heavy-angle and section poles.

terminal clamp is not used, its place being taken by a special bell-mouth parallel-groove type clamp (Fig. 4).

Fig. 5 shows the arrangement of a newly developed and (to date) very successful design for a combined h.v. and l.v. distribution line. At this point it is perhaps not inopportune to mention that the successful develop-

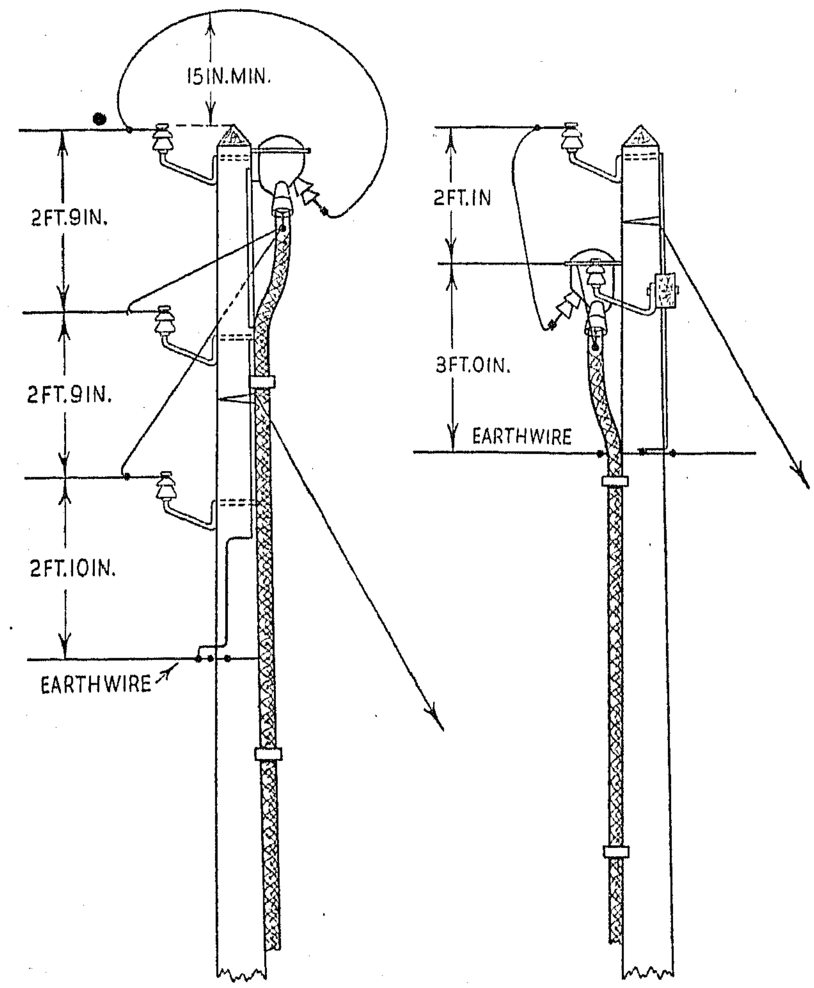


Fig. 3.—Arrangement for terminal poles.

ment of this type of construction has been made possible by the generous co-operation of the Postmaster-General and the Electricity Commissioners with the engineering department of Edmundsons' Electricity Corporation. The agreed maximum operating voltage for this construction is 6·6 kV to earth, and details of the design are outlined below.

(3) H.V./L.V. CONSTRUCTION

The original idea behind the design was to enable additional feeding points to be provided on existing l.v. overhead networks at a low cost by erecting an h.v. line on existing l.v. poles. The reduction from $\frac{3}{8}$ in. to

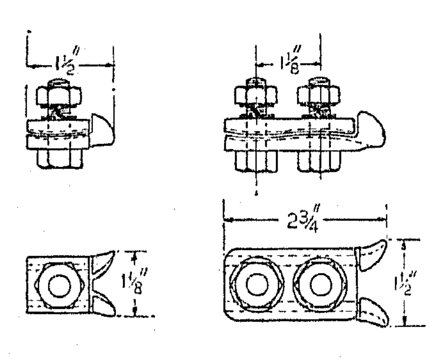


Fig. 4.—Bell-mouth parallel-groove clamp.

$\frac{3}{16}$ in. radial ice loading for h.v. conductors is a major factor in facilitating this design.

Single-phase schemes will be found to satisfy a big

proportion of small rural networks. Existing networks which have been made 3-phase to cope with existing loads can often be altered to single-phase with this type of construction, phase conductor A of the old 3-phase l.v. system being reinsulated for high voltage. Fig. 6 shows typical arrangements for reconstruction from l.v. to h.v./l.v. for both single- and 3-phase schemes.

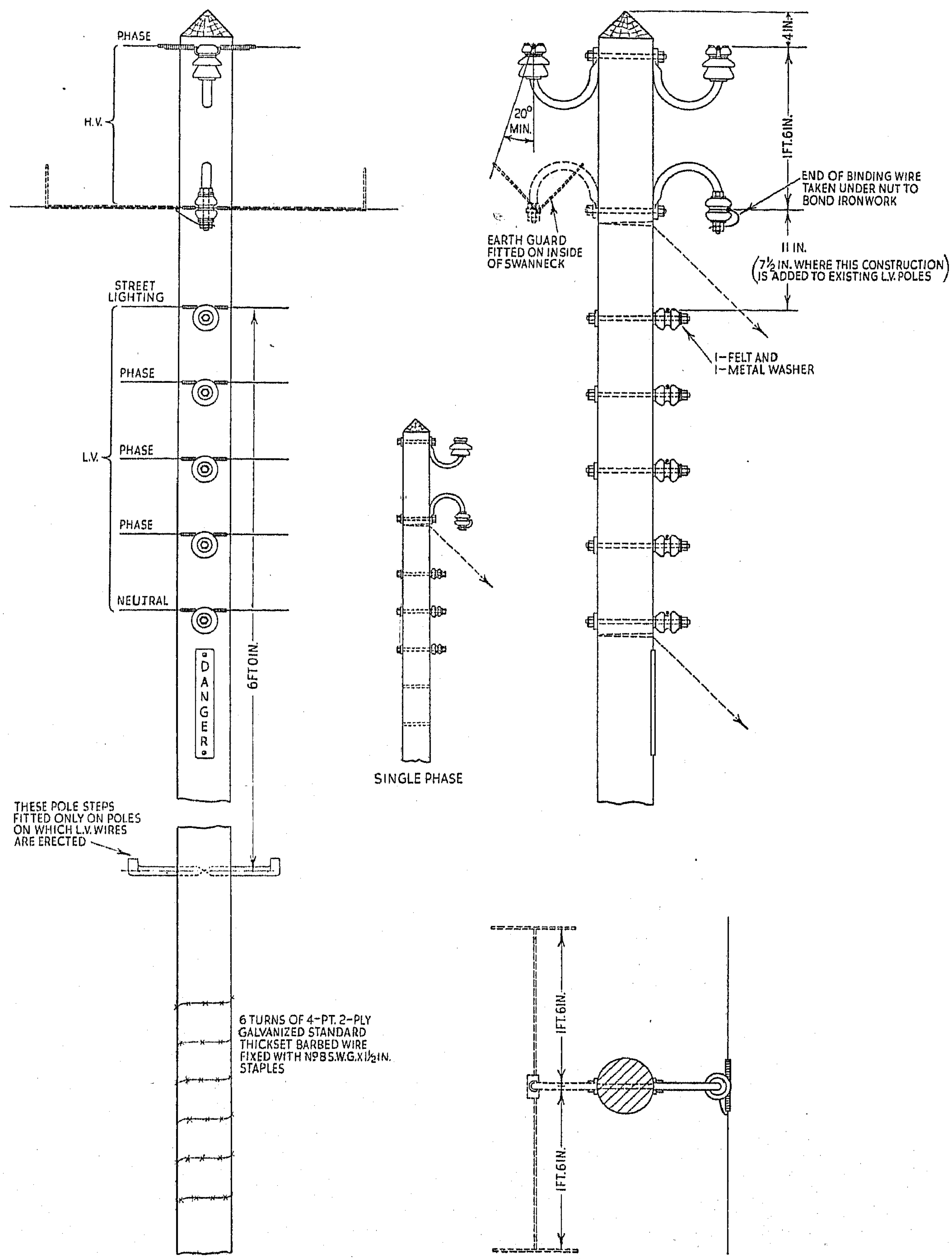


Fig. 5.—Combined h.v./l.v. (new schemes).

In order to make the design successful for the purpose intended, it was obvious that the approval of a relaxation in the standard regulations for h.v. lines was very necessary, and in this respect the Electricity Commissioners have, by giving concessions, enabled a big stride forward to be taken in rural electrical development. The same may be said in connection with the provisions of the Post Office Regulations E.-in-C. 231 (Memorandum on Protection of Post Office Lines from H.V. Power Lines), particularly as l.v. lines are generally erected nearer to P.O. telegraphs than is permitted by these regulations for h.v. lines. The ready co-operation of the Engineer-in-Chief's Department of the Post Office in the experi-

ments, tests, and negotiations necessary in order to draw up, confirm, and approve, the revised Regulations (now covered by Form E.-in-C. 229) has proved to be of paramount importance, and supply authorities operating rural networks are grateful to the P.M.G. for the relaxation now approved.

Some examples of combined h.v./l.v. pole construction are given in Figs. 29A–29F (pages 53 and 54).

The salient points in design which differ from past normal practice are:—

Given by the Postmaster-General:—

(1) Reduced separating distances between h.v. (not exceeding 6·6 kV to earth) lines and P.O. lines.
(2) Attachment of P.O. subscribers' lines to power-line poles.
(3) Attachment of l.v. service wires to P.O. poles.
(4) Reciprocal use of P.O. and power-line poles for flying-stay purposes.
(5) Concessions as to details of cradle guardings, etc.

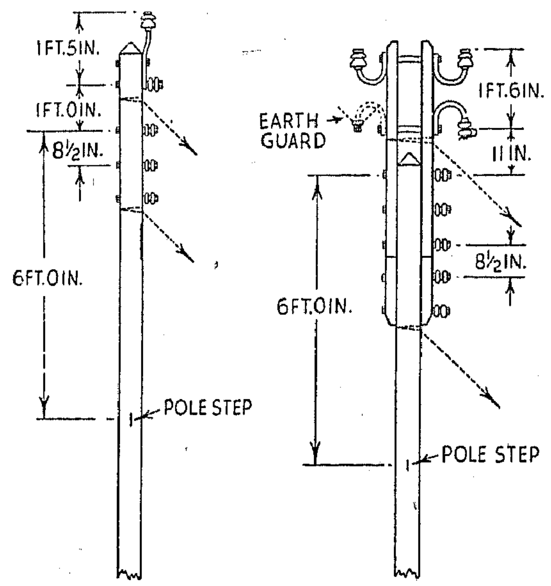


Fig. 6.—Combined h.v./l.v. (reconstruction of existing l.v. lines).

Given by the Electricity Commissioners:—

(1) Reduction in radial thickness of ice loading, to be allowed on h.v. conductors, from $\frac{3}{8}$ in. to $\frac{3}{16}$ in.
(2) Modification of certain restrictions regarding special protection where h.v. conductors are erected along or across roadways.
(3) Relaxation of requirements where h.v. and l.v. lines are erected on the same poles.

(4) FULFILMENT OF QUALIFICATIONS FOR THE IDEAL RURAL LINE

(a) Flexibility

The advantage of flexibility is readily apparent for lines erected along roadways and lanes, and also in agricultural and wooded countryside, where, in order to facilitate wayleaves, it is often necessary to carry the route along hedgerows and fences as far as practicable.

Flexibility is obtained by using small copper conductors, the line tensions for which, at 40° F. for each conductor, are:—

0·04 sq. in., 597 lb. on 400-ft. span basis.
0·025 sq. in., 296 lb. on 300-ft. span basis.

The equivalent line tension for 7/14 S.W.G. steel (60-ton quality) is about 1 450 lb. per conductor on a 500-ft. span. If 80-ton quality steel is employed, the line stresses are again increased, necessitating greater expense at line deflection points. The risk from vibration and crystallization when high tensions such as these are employed with small steel conductors, must not be overlooked.

(b) Isolated Supplies

The possibilities of the combined h.v./l.v. design in affording a ready means of giving an l.v. service to isolated consumers are immediately apparent, and the necessity to run comparatively long lengths of l.v. mains, with possible future voltage-loss troubles, is eliminated. A small transformer erected on the pole nearest to the service position fulfils requirements, and yet generally means reduced capital costs.

(c) Margin for Development of Load

Experience is now showing that "thin" areas which lack public utility services and depend upon oil and coal only for light, cooking, and heating, may, in the near future, saturate small-capacity steel-conductor lines. To cope with this increasing demand some authorities have already been faced with the necessity of installing voltage regulators, reconstructing the h.v. overhead line, or additional h.v. feed points in order to provide the requisite satisfactory voltage regulation. This condition will have to be faced increasingly as time goes on, and it is therefore very desirable that any departure from present general standard designs should incorporate considerably increased carrying capacity.

Figs. 7 and 8 have been prepared to show the voltage loss per mile of line for various types of conductor. An examination of these graphs clearly indicates the very poor electrical properties of steel as a conductor. The voltage loss on the 7/14 S.W.G. steel conductor is five times greater than the loss on 0·025-sq. in. copper. This fact alone is a major reason for developing a design which is suitable for incorporating copper conductors at a cost not exceeding, if possible, that of steel lines.

The slight curve in the line drawn for the steel conductor is due to the magnetic properties of steel which cause an increase in resistance and internal reactance with rising current density. These properties cannot be usefully calculated with accuracy owing to varying methods of manufacture.

From these graphs it will be observed that approximate maximum loads, as shown in Table 1, could be transmitted over 10 miles of line for 5 % voltage loss.

This Table serves as a useful ready guide to the capacities of the various systems. For single-phase systems the capacity is half that given in Table 1.

(d) Low Initial Cost

The reduced ice loading which may now be allowed for on small conductors reduces sag, pole height, and pole diameter. A further advantage which may be gained

by using small copper conductors is the simple, but in this country not very common, method of eliminating expensive disc type tension or strain insulator sets and fittings at terminal section, and angle positions, and using pin-type insulators as a substitute. This of course can only be done because the ultimate tension in the conductor under worst conditions would not, even in the case of 0·04-sq. in. copper, exceed 1 200 lb. It is only necessary to provide a pin insulator fitting having an ultimate strength of 3 000 lb. in order to deal with this

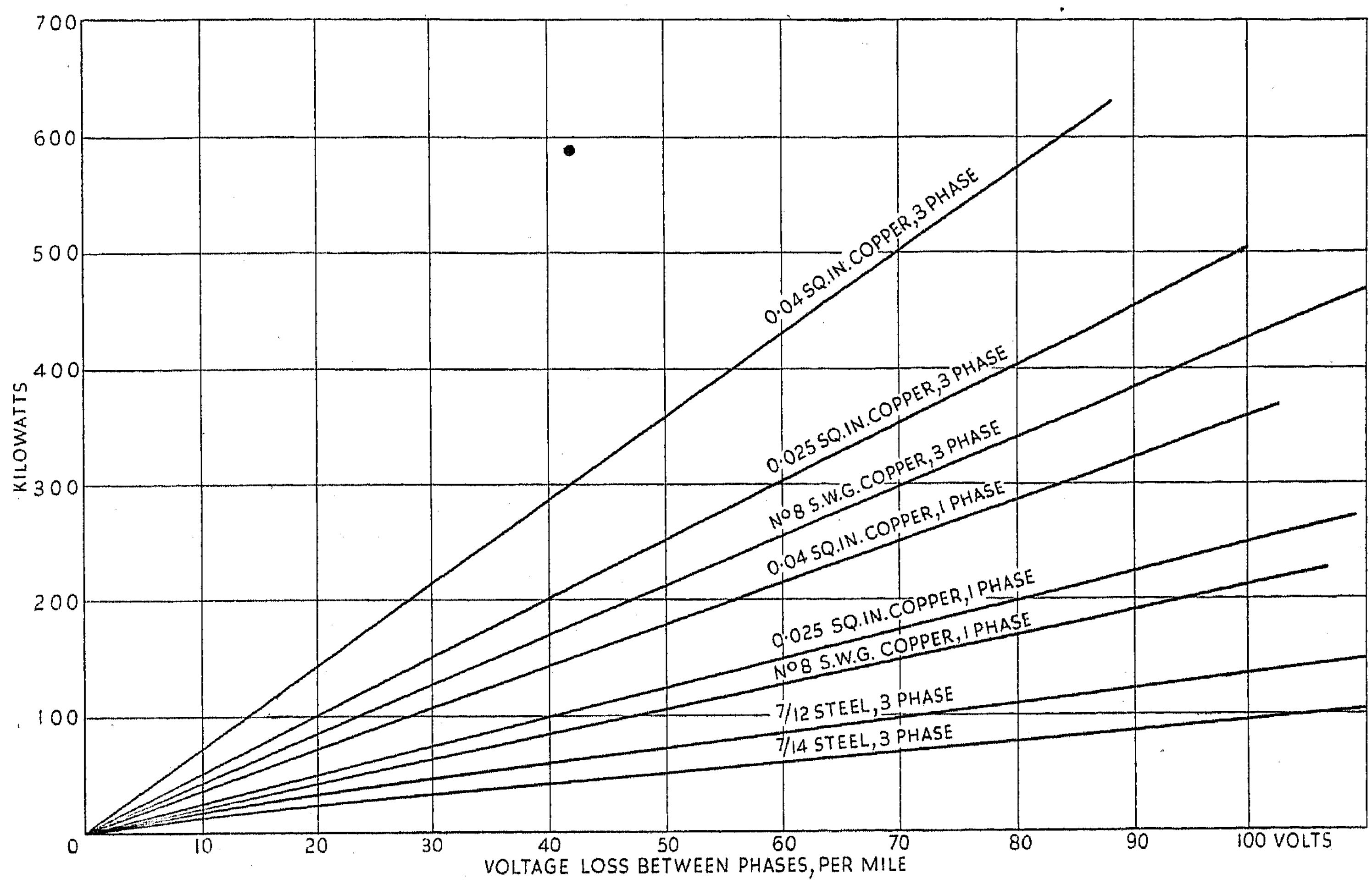


Fig. 7.—Voltage loss.
11 kV, 50 c./sec., 0·8 power factor, 33 in. spacing.

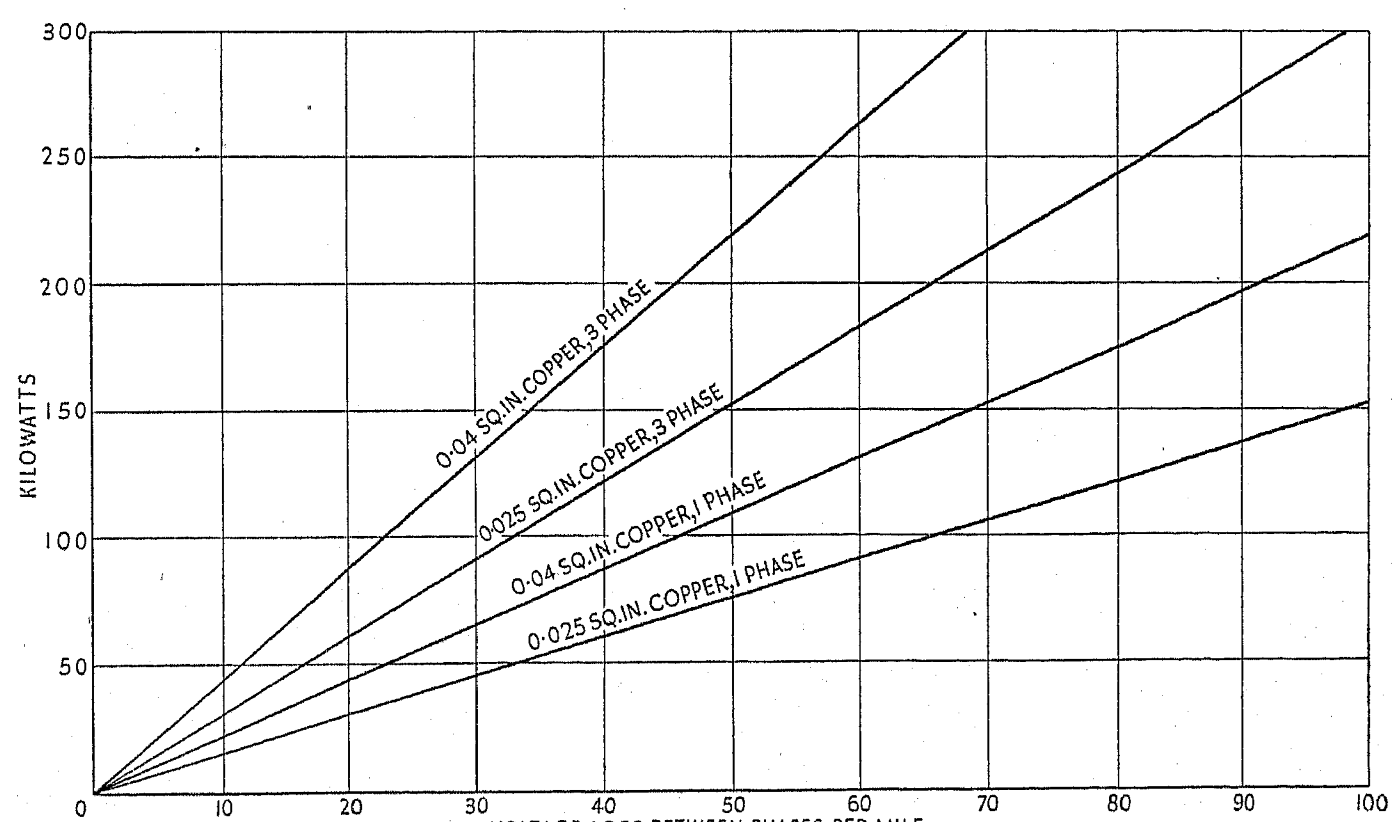


Fig. 8.—Voltage loss.
6·6 kV, 50 c./sec., 0·8 power factor, 18 in. spacing.

load and provide the statutory factor of safety of $2\frac{1}{2}$ for steelwork.

The general lightness of construction, standardization of component parts, low physical stresses, the elimination of heavy terminals and section fittings, indicate low initial cost.

(e) Reliability and Low Maintenance Costs

In the designs, care has been taken to eliminate, as far as possible, the risk of trouble from birds, and yet at the same time eliminate the necessity for insulated guards. In the case of the 11-kV line this has been done by allowing the top of the insulator to stand 3 in. above the shank. The twisting or tipping of insulators is prevented by seating the vertical side of the swan-neck in a $\frac{3}{4}$ in. deep gouging in the pole, thereby ensuring rigidity in service. In order to prevent bird trouble on the h.v./l.v. design the steelwork carrying the live phase insulators is unearthed.

As component parts involving metal-to-metal contacts have been kept down to a minimum, and as the small conductors impose only comparatively light stresses on poles, fittings, and stays, low maintenance costs may be reasonably expected. A much longer life of good service may be expected from copper than from steel conductor lines.

(f) Simplicity of Design

As far as possible, swan-neck type construction is employed throughout the designs, and the small conductors employed enable very light single poles to be used. Except under exposed conditions it is practicable to dispense with kicking blocks, and foundation depths of 5 ft. will be quite satisfactory in ordinary ground for poles up to 32 ft. long (overall).

(g) Inconspicuousness

Short poles and the absence of large cross-arms provide a neat appearance, and the ability to follow hedgerows and to avoid the felling of many trees enables a line to be erected with the least possible interference with local amenities.

(5) COPPER CONDUCTORS

For equivalent cross-sectional area, copper has roughly 8–10 times the carrying capacity of steel, the actual proportion depending upon the current density in and the electrical characteristics of the steel. Copper conductors offer a much longer life than steel.

Table 1

7/14 S.W.G. steel;	11 kV,	3-phase,	60 kW at 0·8 power factor, or	750 kVA-miles.
0·025-sq. in. copper;	6·6 kV,	3-phase,	100 kW at 0·8 power factor, or	1 250 kVA-miles.
0·025-sq. in. copper;	11 kV,	3-phase,	280 kW at 0·8 power factor, or	3 500 kVA-miles.
0·04-sq. in. copper;	6·6 kV,	3-phase,	140 kW at 0·8 power factor, or	1 750 kVA-miles.
0·04-sq. in. copper;	11 kV,	3-phase,	400 kW at 0·8 power factor, or	5 000 kVA-miles.
0·1-sq. in. copper;	400 V,	3-phase,	1·04 kW at 0·8 power factor, or	13 kVA-miles.

Until the Electricity Commissioners made the recent concession in ice loading, small copper conductors suffered the disadvantage of providing for a heavy radial ice loading in comparison with actual conductor diameter. It is perhaps opportune here to appraise the value of the reduction from $\frac{3}{8}$ in. to $\frac{3}{16}$ in. radial ice, and Table 2 provides interesting comparisons.

Table 2

Conductor	Span	Breaking load	Tension at 122° F.		Tension at 40° F.		Breaking load. Ratio to tension at 40° F.	
			Old	New	Old	New	Old	New
	ft.	lb.	lb.	lb.	lb.	lb.		
7/12 S.W.G. steel (60 tons) ..	600	7 100	1 365	—	1 975	—	3·6	—
0·1-sq. in. copper	600	6 065	1 142	—	1 410	—	4·3	—
7/14 S.W.G. steel (60 tons) ..	500	4 400	625	955	935	1 450	4·7	3·03
0·04-sq. in. copper	400	2 400	252	413	294	597	8·15	4·02
0·025-sq. in. copper ..	300	1 517	108	195	124	296	14·0	5·12

This Table clearly shows the penalty suffered by small copper conductors before the revised loadings were permitted, the normal line tensions being quite disproportionate to the breaking loads.

It will be noted that this paper deals only with stranded conductors, although solid conductors as small as No. 8 S.W.G. are permitted by the Commissioners' Regulations. The advantages of stranded over small solid conductors may, for practical purposes, be taken as (*a*) greater flexibility, (*b*) less tendency to crystallize at points of support due to vibration, and (*c*) less risk of serious damage during line construction. When $\frac{3}{8}$ in. ice loading had to be provided for when stringing conductors, (*a*) and (*b*) could be ignored because of the low working tensions employed, so that a number of lines

are now existing which incorporate No. 7 and No. 8 S.W.G. copper conductors in order to obtain the advantages mentioned in the next paragraph.

Advantages gained by the use of solid conductors are (*a*) reduction in wind and ice loadings when compared with stranded conductors of equivalent cross-sectional area, (*b*) a corresponding reduction in wind loading on poles, and (*c*) saving of the cost of stranding. The higher tensions which may now be employed by allowing for $\frac{3}{16}$ in. instead of $\frac{3}{8}$ in. ice loading, makes it advisable to sacrifice these advantages in order to ensure flexibility and absence of crystallization referred to above.

(6) COMPARATIVE COSTS

The foregoing brief description shows that a line of light construction can be built which combines flexibility of route and comparatively low physical stresses with relatively high conductivity when compared with steel-conductor lines.

Generally speaking, it is safe to say that one is on safer ground with a preliminary estimate for a short-span than for a long-span line unless the route has been previously surveyed and plotted and quantities taken out.

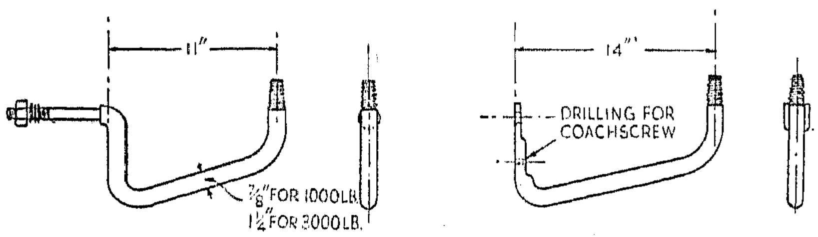


Fig. 9.—Typical swan-neck brackets (11-kV lines).

If the object of low cost is to be achieved, relatively straight lines are essential, and it is also generally considered necessary to maintain long spans when using steel conductors, but an extra pole inserted, due perhaps to wayleave difficulties or contour, creates a greater proportional increase in cost per mile than does an extra pole on a short-span line. Similarly, the introduction of section or make-off points on steel lines, involving the use of strain insulators, will again increase costs disproportionately. Therefore, costs for short-span lines will not vary or fluctuate to the same extent as for long-span lines.

The construction of many miles of light-construction lines has proved that this type of line employing 0·025-sq. in. copper can be erected for inclusive costs which are generally lower than costs for long-span steel lines, thereby justifying from cost alone the use of copper conductors. This means that without increasing overall costs it is possible to obtain big savings in line losses and much greater scope for ultimate development within the area surrounding the route of the line or network.

(7) CONSTRUCTION (11-kV LIGHT-CONSTRUCTION LINES)

For straight-line and slight-angle positions, swan-necks (Fig. 9) having an ultimate strength of 1 000 lb. or 400 lb. maximum working load are used, and 3 000 lb. ultimate or 1 200 lb. maximum working load swan-necks for terminal and more acute angle positions. A 1 000-lb. swan-neck can be made up from $\frac{7}{8}$ in. dia. by 38–45 tons quality steel, and the 3 000-lb. swan-neck from $1\frac{1}{4}$ in. diam. by 38–45 tons quality. The shanks should be reduced to a common diameter, say $\frac{7}{8}$ in., in order to maintain uniformity of pole drillings, etc.

At positions where duplicate insulation is required, a double or branched swan-neck (Fig. 10) is used.

(8) CONSTRUCTION (H.V./L.V. CONSTRUCTION)

(a) Bonding

The concession given by the Electricity Commissioners regarding earthing and bonding of steelwork for the h.v./l.v. design eliminates the risk of trouble from birds,

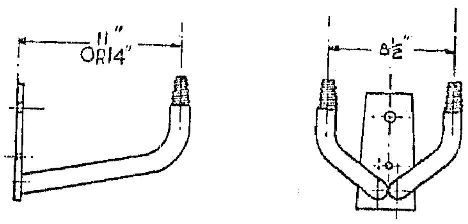


Fig. 10.—Duplicate swan-neck (11-kV lines).

and enables self-centring swan-necks to be used as shown in Fig. 11. It will be noted that the steelwork supporting the earthed phase is bonded to the earthed conductor in order to prevent the pole beneath the earthed h.v. wire becoming charged to a dangerous voltage in the event of failure of a live h.v. phase insulator.

(b) Cantilever Loads

At angle and terminal points the position for the stay may introduce cantilever loads at the pole top, and care should be taken to ensure that adequate pole-top diameters are obtained at any such position. Fig. 12

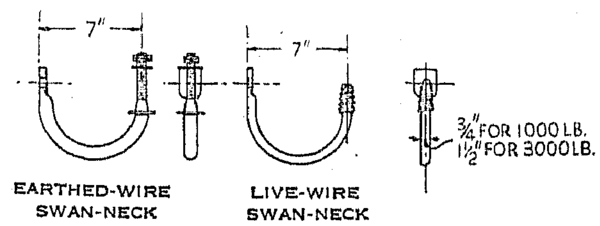


Fig. 11.—Swan-neck brackets (h.v./l.v. lines).

shows the pull on angle poles for varying line deflections with conductors fully loaded and also at 40° F. without wind and ice.

(c) Road Crossings, etc.

With the exception of small earth guards, the Electricity Commissioners do not call for duplicate insulators, arcing horns, bridles, or any other special arrangement where this type of line is erected along or across roadways. At these positions, however, it is necessary to erect the light "V" type earth guard shown in Fig. 28, the guard being necessary only beneath the live h.v. conductor on the side of the pole opposite to the earthed phase. The earthed phase wire itself acts as an adequate guard for the live phase wire immediately above it.

(d) Pole Steps

Pole steps are fitted at a point 6 ft. below the highest l.v. conductor. This has been done at the request of

the Electricity Commissioners in order to minimize the possibility of a linesman going too high up the pole and making accidental contact with a live h.v. conductor. Linesmen should be instructed not to ascend above these steps, nor use a ladder which reaches above them, unless they are working on a "dead" section.

(e) Bird-Trouble Risks

As mentioned in (*a*) above, the earthing of steelwork is omitted. The only exception to this rule is in the permanent single-phase design where the pole-top fitting is automatically bonded, but in this case there is no risk of bird trouble.

(f) Conductors

It is recommended that h.v. conductors should be limited to two sizes. These are 0·04-sq. in (7/·086 in.) or 0·025-sq. in. (3/·104 in.) copper, and should preferably be tensioned to give the same sag as the l.v. conductors referred to below.

0·06-sq. in. (7/·105 in.) copper appears to be most suitable for the l.v. conductors in normal schemes. Tensioning of conductors will vary according to the conditions prevailing in individual schemes, but a reasonable maximum is about 440 lb. for 0·06 sq. in., which gives a sag of 1 ft. over a span of 120 ft.

(g) Span Lengths

It is, of course, impossible to lay down hard-and-fast rules regarding span lengths, but 120 ft. will generally be found to be a satisfactory span for villages and ribbon development. Where development is thin or scattered the spans may be increased to 135–150 ft. or thereabouts.

Fig. 13 provides increased spacing of conductors, and is designed to reduce costs for sections of line erected through fields or along undeveloped country lanes and roads where the probability is remote of l.v. conductors being required in the near future. Span lengths for this type of line should not be more than 300 ft., so that in the event of l.v. conductors being added at a later date this can be carried out by the introduction of intermediate poles, thereby reducing the span length to a maximum of 150 ft.

(h) Type of System

Single-phase schemes will be found to satisfy the major proportion of small rural networks, and in order to keep as low as possible the ratio of cost to route length it is preferable to employ single-phase. By attaining this aim it is possible to service a much wider area for the same capital cost of a 3-phase network covering less ground. One further point in favour of single-phase development is the fact that a given capital expenditure will, by providing a greater route length of distributor in comparison with 3-phase, enable additional sources of revenue to be tapped, thereby either:—

(i) Providing a higher percentage figure for revenue to capital expenditure,

or (and preferably)

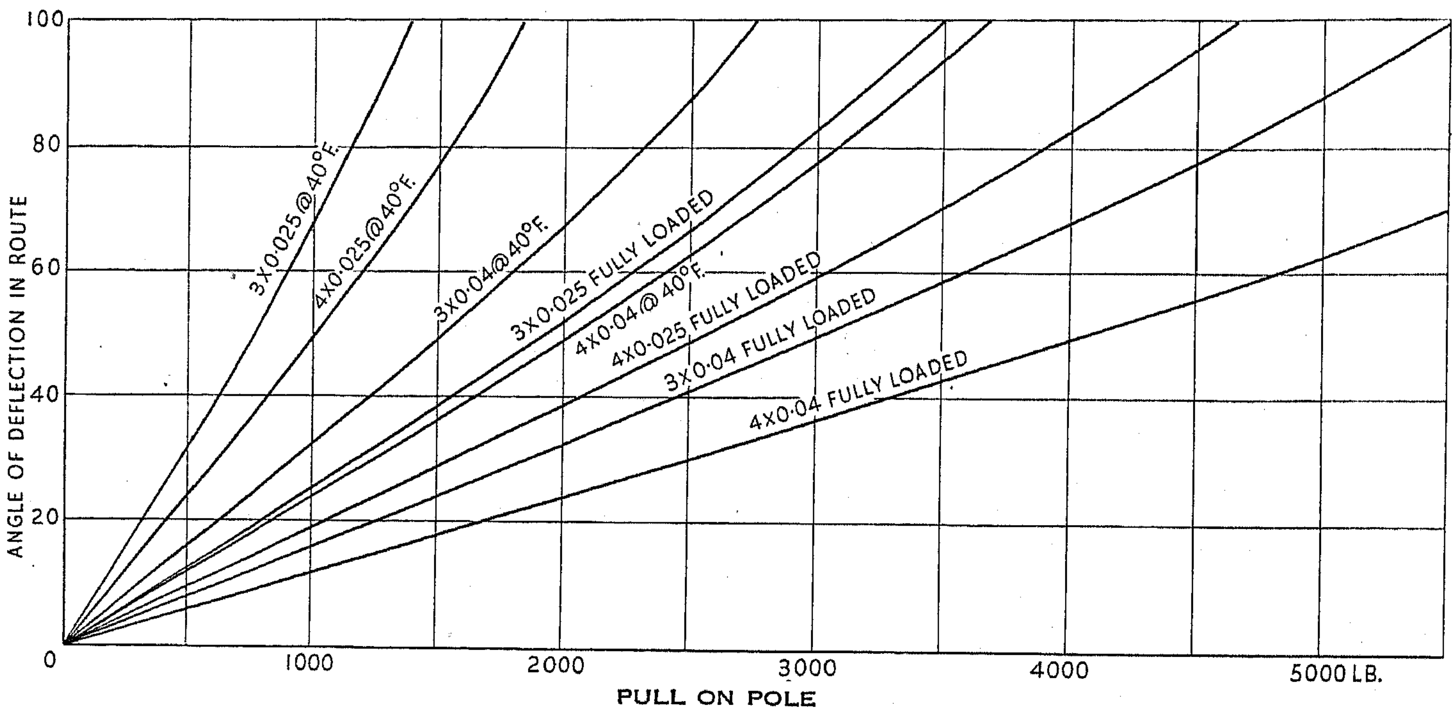


Fig. 12.—Pull at angle poles (h.v. lines). This also represents maximum limits for h.v. on h.v./l.v. lines.

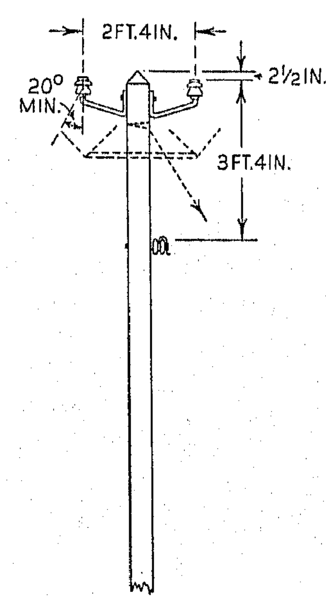


Fig. 13.—Long span h.v. (for future h.v./l.v.).

(ii) Maintaining the smaller revenue to capital percentage, which would have applied in a 3-phase scheme, and by so doing extend the network into thinner parts of the area which otherwise would not have been self-supporting.

With the exception of the permanent single-phase arrangement, each h.v./l.v. design is drawn up to allow for its initial construction as a single-phase network, with provision for easy conversion to 3-phase at a later date should development of load make this necessary. As the additional cost of making provision for future 3-phase is only about £15 per mile more than permanent single-phase, it is generally wise to incur this small extra cost in the majority of schemes.

Where the motor load would normally necessitate a 3-phase l.v. scheme, the l.v. side of h.v./l.v. systems can frequently be carried out by single-phase because the facility with which step-down transformers can be installed at positions adjacent to load points eliminates the line losses which so often restrict the use of single-phase l.v. systems. Single-phase low voltage should also be used as far as possible on lines where the h.v. system passing through is necessarily 3-phase.

(9) PROXIMITY OF H.V./L.V. LINES TO P.O. TELEGRAPHS

Low-voltage overhead lines are generally erected nearer to P.O. lines than is permitted by the P.O. standard regulations for h.v. lines. The issue by the Post Office Engineering Department of Form E.-in-C. 229 (Memorandum for the Protection of Post Office Lines from Rural H.V. Overhead Power Lines of Light Construction) has helped very considerably in the successful development of this form of construction.

In order that the clearances of 6 ft. and 12 ft. referred to in P.O. Form E.-in-C. 229 may be readily checked, a turnover clearance chart has been devised as shown in Fig. 15. Accurate results can also be readily obtained by the use of the small slide rule shown in Fig. 14.

As the memorandum (Form E.-in-C. 229) is in itself self-explanatory, it is unnecessary to make further comments in this paper regarding its application, except to suggest that full advantage be obtained and offered in connection with the reciprocal or joint use of poles for services, flying stays, etc. New schemes should be planned in order to facilitate this arrangement.

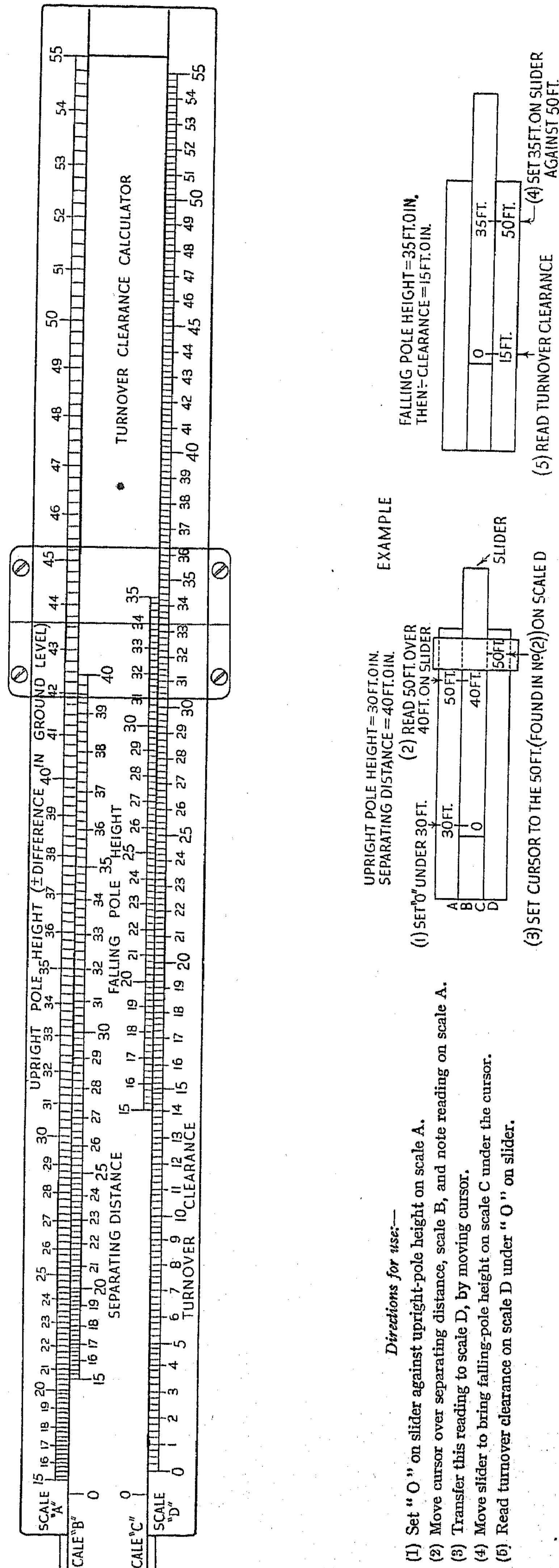
(10) EARTHING METHODS ON H.V./L.V. SCHEMES

(a) H.V. System

The h.v. system must only be earthed at the h.v./l.v. step-down transformer. The construction outlined in this paper provides for the earthing of one side of the single-phase h.v. system, and in the case of 3-phase schemes one h.v. phase is earthed, the red phase being chosen as a standard for this purpose. The object of this method is to allow an earthed wire to be run along the line without the necessity for running an additional wire for earthing purposes.

(b) H.V./L.V. Transformers

The tank and sheaths of the lead-covered h.v. leads must be earthed at the transformer pole, and the earth



Directions for use:—

(1) Set "O" on slider against upright-pole height on scale A.
(2) Move cursor over separating distance, scale B, and note reading on scale A.
(3) Transfer this reading to scale D, by moving cursor.
(4) Move slider to bring falling-pole height on scale C under the cursor.
(5) Read turnover clearance on scale D under "O" on slider.

Fig. 14.—Slide-rule for calculating turnover clearance.

Adjustments for top conductors fixed 4 ft. from centre line of falling pole.

Height of top conductor on falling poles	16′	18′	20′	22′	24′	26′	28′	30′	32′	34′	36′	38′	40′	42′
From value of X or Y obtained from the curves, subtract	4½″	4″	3¾″	3¼″	3″	2¾″	2½″	2½″	2¼″	2¼″	2″	2″	2″	1¾″

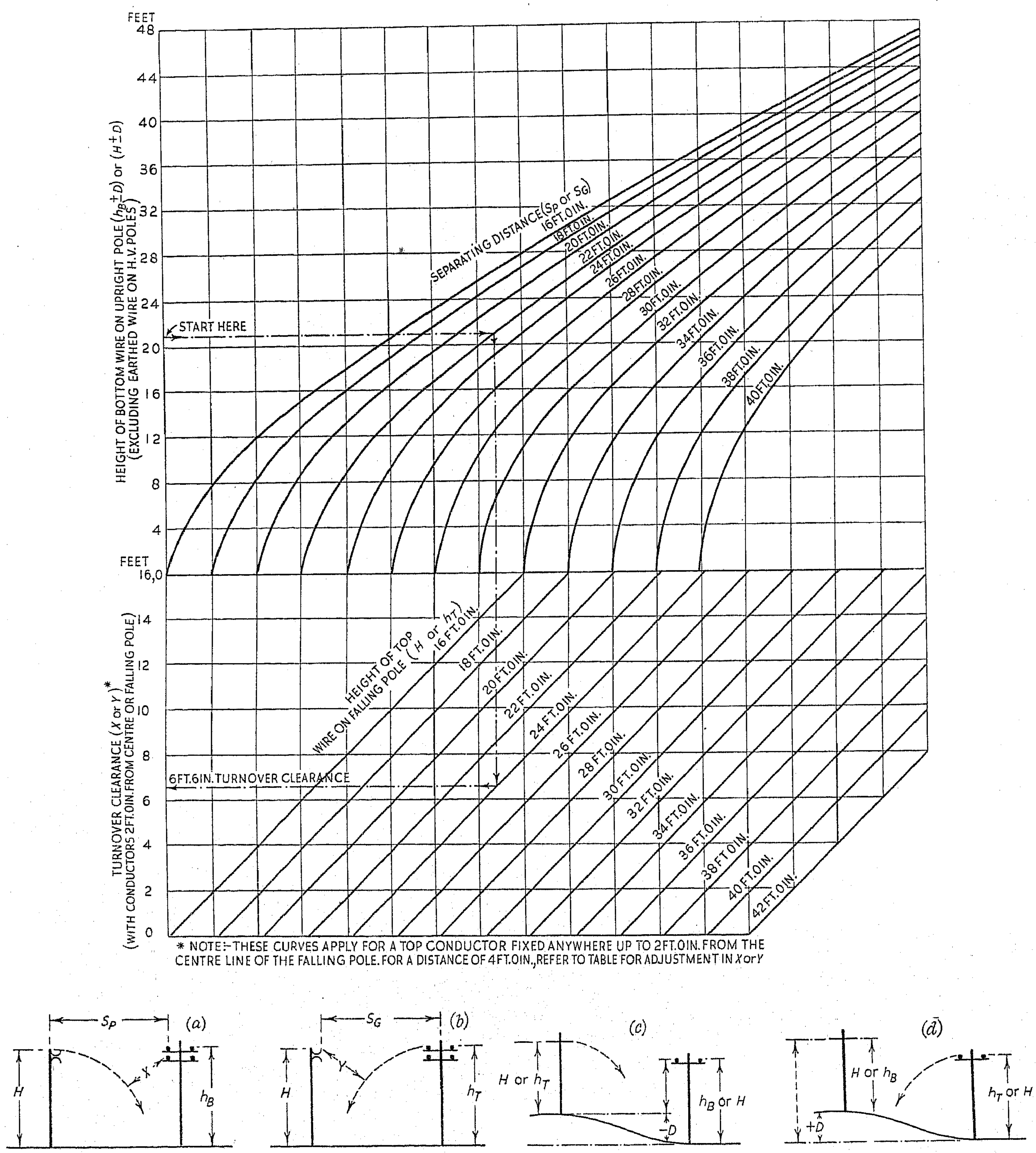


Fig. 15.—Turnover clearance for h.v./l.v. construction.

(*a*) Power-pole falls. (*b*) P.O. pole falls. When (*c*) pole at higher level or (*d*) lower level falls:— Subtract D from, or add D to, height on upright pole (h_B or H). } For variations in ground-level.

resistance value must be low enough, when considered in conjunction with the earth for the h.v./h.v. transformer, to pass at least twice the current necessary to operate the fuse or switch controlling the h.v. line.

(c) L.V. Neutral

Earthing of the l.v. neutral should be carried out in the usual way, preferably at the pole adjacent to the transformer pole.

(11) ARRANGEMENT OF TRANSFORMER POLES

(a) Connections

Fig. 16 shows a typical arrangement of h.v./l.v. transformer pole. The transformer-to-line leads of the live phases are 0·193 in. (0·029 sq. in.) solid-core paper-insulated lead-covered single cable, the earthed phase lead being single under-eaves-type cable. Solid core-type

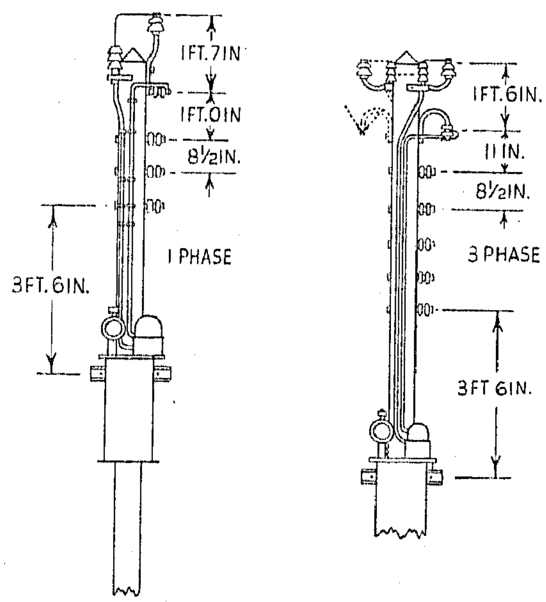


Fig. 16.—Transformer pole (h.v./l.v. distribution).

paper-insulated cable has been used as the result of a number of tests which were carried out in order to ascertain the most suitable type of cable for this purpose, with particular reference to the elimination of radio interference, which was generally found to be introduced if stranded-core or cambric-insulated cable was used.

(b) Sealing Ends

Porcelain sealing-ends are used for terminating the line end of live phase leads. Fig. 17 indicates the type of inexpensive sealing-end which has been successfully developed for this type of line, and it has been found to be good practice to make up the complete sealing-end and lead in the workshop or stores in order to ensure good workmanship and to avoid the necessity for doing the work on site under less favourable conditions.

(c) Isolating

For isolating the h.v. side of the h.v./l.v. transformers special live-line connectors are employed, as shown in Fig. 18. The flexible lead used is 7/·029 in. copper about 20 in. in length, and is drawn through a short length of copper tube secured to the sealing end. This is done in order to keep the flexible lead away from the insulator sheds, and also to provide a rigid position to which the live-line connector may be secured when in the isolated position.

The live-line connectors are operated by means of an operating rod specially designed for this purpose, and for use when the connection or disconnection is to be made to a live line.

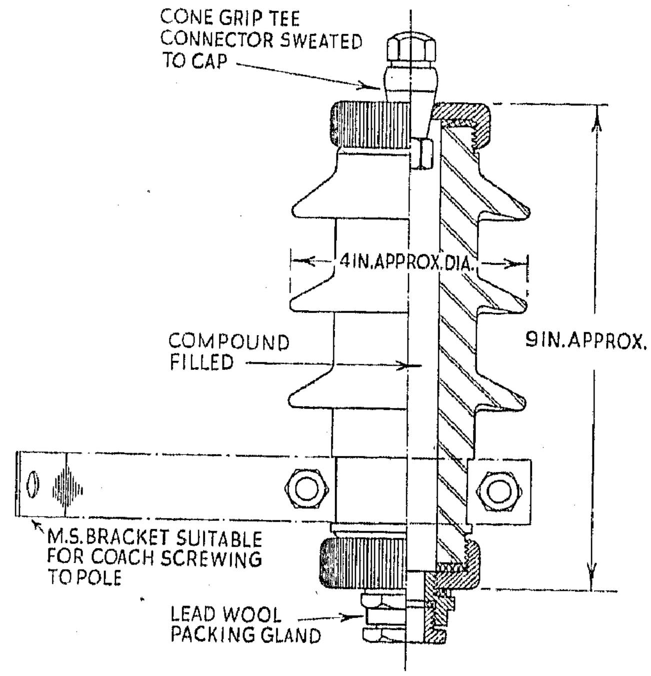


Fig. 17.—Sealing end.

(12) PARALLELING SECTIONS OF LINE ON H.V./L.V. SCHEMES

Each h.v./l.v. transformer should normally be connected to feed only into its own l.v. distribution section. In special cases, however, a light fuse may be inserted on any suitable section pole in order to parallel transformers in cases where it is considered necessary to permit two or more transformers to feed into the same network. Where paralleling of transformers is permitted it is of course necessary to remove all neutral earth links except one, unless the Electricity Commissioners' permission for earthing at more than one point has been obtained.

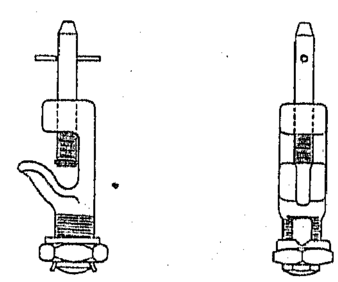


Fig. 18.—Live-line connector.

(13) ANNUAL COST OF H.V. LINE LOSSES

Line losses are, all too frequently, considered only from the viewpoint of voltage loss at maximum load, and the annual cost of line losses, which is a charge against revenue account, is not given the attention its importance merits. This may be due, in part, to difficulty of forming a true value of the losses, and also to the fact that until recent years most distribution schemes could be carried through with a fair amount of copper

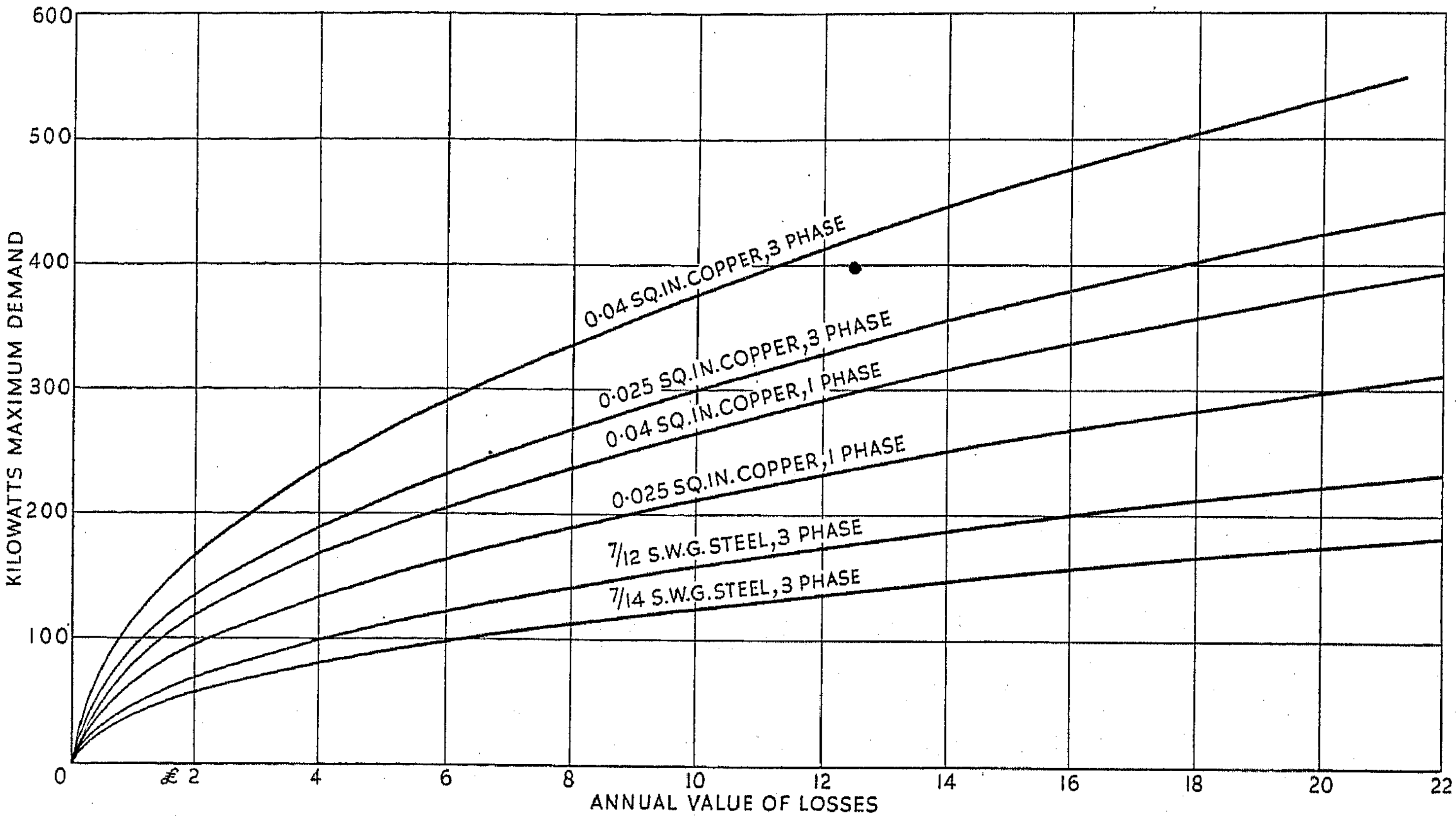


Fig. 19.—Annual cost of line losses per mile.

Basis:—11 kV, 50 c./s.; £3 10s. per kW max. demand; 0·225d. per kWh; system load factor = 20 %.

for future development. The electrification of "thin" areas, and the use of steel conductors, has made this question more acute, and although it is practically impossible to calculate accurately the annual value of losses, because the load factor of the losses is far lower than that of the load, Figs. 19 and 20 have been prepared to show an approximation of the various costs and should prove a useful guide.

There is a natural tendency to build the least expensive type of line in "thin" areas, and this usually implies lines of high impedance value and low carrying capacity. It is interesting, therefore, to use Fig. 19 in order to draw a few comparisons between various types of line. The curve for 7/14 S.W.G. steel shows 100 kW of load producing an annual line loss of £6·2 per annum per mile of 11-kV 3-phase line which, capitalized at 10 %, amounts

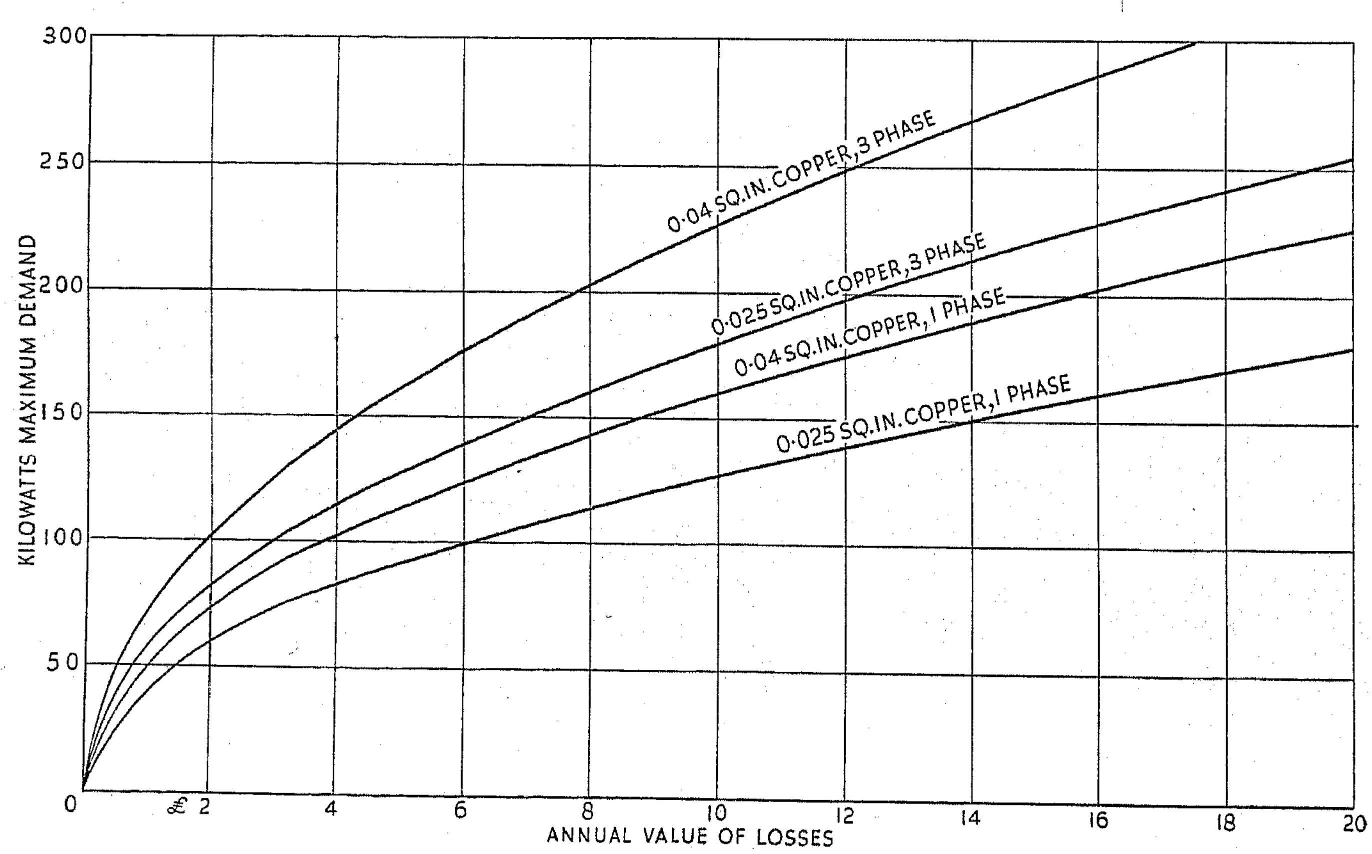


Fig. 20.—Annual cost of line losses per mile.

Basis:—6·6 kV, 50 c./s.; £3 10s. per kW max. demand; 0·225d. per kWh; system load factor = 20 %.

to £62 per mile. For 0·025-sq. in. copper the loss on 100 kW is shown to be £1·1 per mile, which, capitalized, is £11 per mile of line. Therefore, on this basis, it is sound economics to build a 0·025-sq. in. copper line even should the cost be £50 per mile higher than for 7/14 S.W.G. steel. From this figure of £50 per mile a deduction may be made to provide for the capitalization of wayleave rentals on the shorter-span line, although any figure so obtained is more than counterbalanced by the maintenance or renewal charge which must be met much earlier on the steel line.

The cost of line losses must, of necessity, be debited against running or revenue account, and, therefore, any portion of this cost which it may be possible to save could be used to pay interest and depreciation on additional capital expenditure, deriving thereby the scope for greater future development without creating an immediate burden on the supply authority.

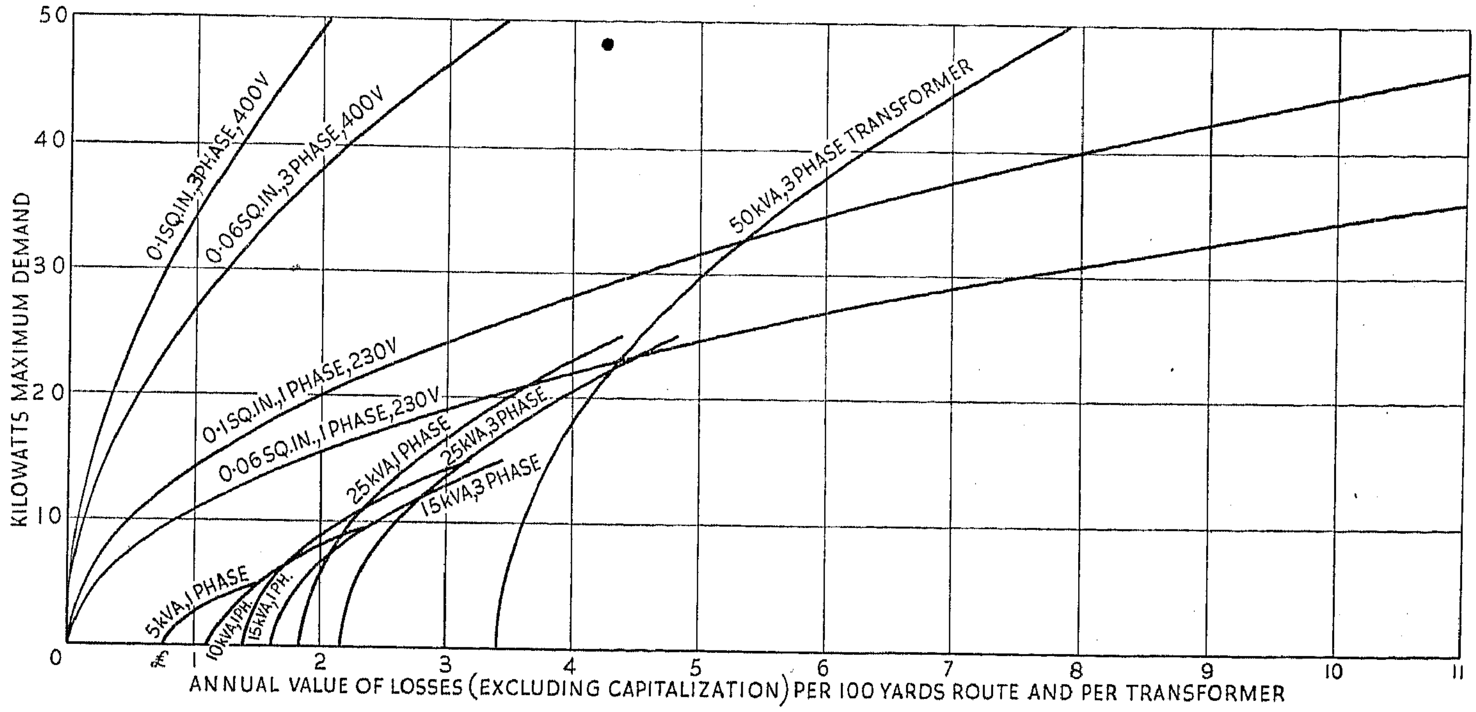


Fig. 21.—Annual cost of losses, l.v. network and transformers, excluding capital expenditure.

Line curves are drawn for max. demand all the way (100 yd.). If max. demand is equally distributed then route length multiplier = 2 (200 yd.). Basis:—£3 10s. per kW max. demand; 0·225d. per kWh; system load factor = 20 %.

(14) ANNUAL COST OF TRANSFORMER AND L.V. LINE LOSSES

The development of combined h.v./l.v. construction has made it necessary to form a scale of values dealing with the extension of l.v. conductors and the installation of additional transformers. To pursue this point to its

Table 3

H.V. Linesman's Sag Chart

Temp.	Tension	Sag (in feet) for various span lengths (in feet)																
		400	380	360	350	340	330	320	310	300	290	280	270	260	250	240	200	150
°F.	lb.																	
122	413	7·74	7·0	6·27	5·93	5·6	5·27	4·96	4·65	4·36	4·07	3·8	3·53	3·27	3·03	2·79	1·936	1·09
110	432	7·30	6·68	6·0	5·67	5·36	5·04	4·74	4·45	4·17	3·89	3·63	3·38	3·13	2·89	2·67	1·852	1·041
100	450	7·11	6·42	5·76	5·44	5·14	4·84	4·55	4·27	4·0	3·74	3·49	3·24	3·0	2·78	2·56	1·777	1·0
90	469	6·82	6·16	5·52	5·22	4·93	4·64	4·37	4·10	3·84	3·59	3·35	3·11	2·88	2·67	2·46	1·705	0·96
80	490	6·54	5·90	5·29	5·0	4·72	4·44	4·18	3·93	3·67	3·44	3·20	2·98	2·76	2·55	2·35	1·633	0·918
70	513	6·24	5·63	5·05	4·78	4·51	4·25	3·99	3·75	3·51	3·28	3·06	2·84	2·64	2·44	2·25	1·560	0·877
60	539	5·95	5·38	4·82	4·56	4·30	4·05	3·81	3·58	3·35	3·13	2·92	2·71	2·51	2·33	2·14	1·487	0·837
50	567	5·65	5·09	4·57	4·32	4·08	3·84	3·61	3·39	3·17	2·97	2·77	2·57	2·39	2·21	2·03	1·411	0·794
40	597	5·36	4·84	4·34	4·1	3·87	3·65	3·43	3·22	3·01	2·82	2·63	2·44	2·27	2·09	1·93	1·340	0·754
30	630	5·08	4·59	4·11	3·89	3·67	3·46	3·25	3·05	2·86	2·67	2·49	2·32	2·15	1·97	1·83	1·270	0·714
22	658	4·86	4·39	3·94	3·72	3·51	3·31	3·11	2·92	2·74	2·56	2·38	2·22	2·06	1·90	1·75	1·216	0·684

0·04 sq. in. copper

Basis:—

Radial ice = $\frac{3}{16}$ in.
Wind pressure = 8 lb./sq. ft.
Breaking load = 2 400 lb.
Stranding = 7/·086 in.
Factor of safety = 2.
Maximum span = 400 ft.

final theoretical conclusions would take too much space to deal with here, and is outside the scope of the more practical and general purposes of this paper. Owing to the widely dissimilar conditions appertaining to different schemes and extensions, it is impossible to prepare a chart or graph of general accuracy, but Figs. 21 and 22 have been drawn up to provide a ready means of determining between the extension of l.v. conductors and the installation of a transformer. The basis for the graph is the same as for Figs. 19 and 20, but, in addition, the cost of losses in Fig. 22 include also for 10 % of capital expenditure to cover interest and depreciation charges.

(on the shorter spans) the margin of difference, after binding-in, between the sag measured at regulation or binding-in temperature and the sag at 122° F. as given in the charts.

The questions of this margin of difference, and the tolerance which should be allowed for all spans which are shorter than the basic span, are dealt with later.

(b) H.V./L.V. Construction

It is true to say that for normal l.v. schemes it is impossible to tension-up conductors to the maximum permissible stress, and it is therefore necessary to adopt a different principle regarding the sagging of conductors from that employed for cross-country 11-kV lines. Individual schemes will occasionally be met which possess special local difficulties, and it is impossible to lay down hard-and-fast rules regarding the stringing of conductors, but, nevertheless, it is possible to give guiding figures for average work, and Table 5 has been prepared for this purpose. The basis is a sag of about 1 ft. for 0·06-sq. in. copper over a span of 120 ft. which produces a tension of 440 lb., the smaller h.v. conductors being pulled up to give the same sag as the l.v. conductors.

Generally speaking, it is preferable to consider Table 5 as providing the minimum sags (or maximum tensions) which should be employed for h.v./l.v. schemes, as increased sags will occasionally be necessary, particularly in villages or along tortuous routes where adequate staying facilities may be difficult to obtain.

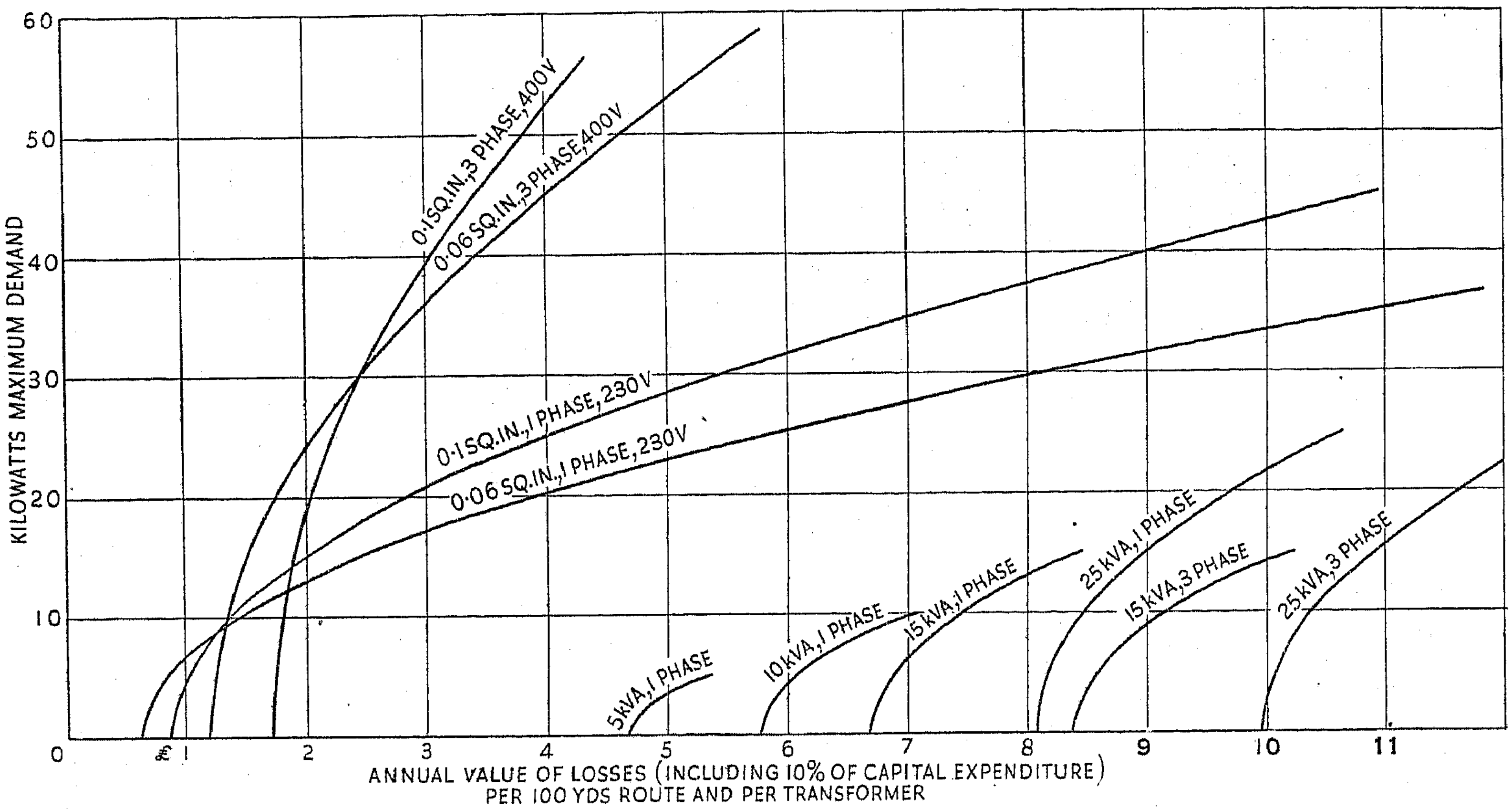


Fig. 22.—Annual cost of losses, l.v. and transformers, including 10 % capital expenditure.

Line curves are drawn for maximum demand all the way (100 yd.). For equally distributed loads, route length multiplier = 2 (= 200 yd.), and total losses are the indicated losses (= 200 yd. route) plus value of curve at zero. Basis:—£3 10s. per kW maximum demand; 0·225d. per kWh; system load factor = 20 %.

For the purposes of Fig. 22, capital expenditure on the l.v. distributors has been taken as simply the cost and erection of l.v. conductors only, and, as regards the transformer, the cost and erection of the transformer only.

(15) STRINGING AND SAGGING CONDUCTORS

(a) 11-kV Light Construction Lines

In the author's opinion the best method to ensure regularly accurate stringing of light conductors is to measure sag instead of tension. For this purpose linesmen's charts (Tables 3 and 4) have been prepared on the basis given at the foot of the charts. The span length given at the head of the first sag or dip column is the basic span length for which the tensions have been calculated. Sags shown for the shorter spans are correct at the moment of regulating, and, therefore, allow the linesman to measure the sag at any suitable span in the section.

If required, linesmen's charts may be compiled on a shorter span basis. This would have the effect of increasing the tension in a conductor and would also reduce

(16) SAG TOLERANCE

It is well known that although, for practical purposes, tension in a conductor is equal in all spans throughout

a section at the moment of binding-in, this condition is not maintained when a change in temperature takes place after the conductors have been bound-in.

Briefly, the position is that the lower the temperature at which conductors are bound-in, the greater will be the difference in sag and tension at 122° F. in relation to the linesman's chart figures for 122° F. The only condition under which a conductor would give sags on varying span lengths each to conform to the linesman's chart at 122° F. would be when the conductor is actually regulated and bound-in at 122° F. As this condition cannot be met, it follows, in order to ensure that the provision of a statutory minimum ground clearance is maintained, that a tolerance on ground clearance must be allowed by the draughtsman or surveyor engaged on plotting pole positions and determining pole heights. The tolerance allowed generally takes the form of a standard addition of 1–2 ft. to the statutory clearance in order to provide for this and other small margins of error, but in order to appreciate the true position for conductors Fig. 23 has been prepared.

For the purpose of Fig. 23 the low figure of 40° F. was taken as a reasonable minimum temperature at which conductor stringing and binding-in is likely to be carried out. Where conductors are tensioned at temperatures higher than 40° F. the sag additional to the linesman's chart figures would grow less until tensioning is done at 122° F., at which point, as mentioned above, the additional sag would be nil.

Table 4

H.V. Linesman's Sag Chart

Temp.	Tension	Sag (in feet) for various span lengths (in feet)												
		300	275	250	245	240	235	230	225	200	175	150	125	100
° F.	lb.													
122	195	5·77	4·85	4·0	3·84	3·68	3·54	3·39	3·25	2·56	1·96	1·44	1·0	0·64
110	205	5·49	4·61	3·8	3·66	3·51	3·37	3·22	3·09	2·44	1·86	1·37	0·953	0·61
100	214	5·26	4·42	3·65	3·51	3·37	3·23	3·09	2·96	2·34	1·78	1·31	0·913	0·584
90	224	5·02	4·22	3·48	3·35	3·22	3·08	2·95	2·83	2·23	1·71	1·25	0·872	0·557
80	236	4·76	4·0	3·3	3·18	3·05	2·92	2·8	2·68	2·12	1·62	1·19	0·827	0·529
70	248	4·54	3·81	3·15	3·03	2·91	2·78	2·67	2·55	2·01	1·54	1·13	0·788	0·504
60	262	4·29	3·61	2·98	2·86	2·75	2·63	2·52	2·42	1·9	1·46	1·07	0·745	0·476
50	278	4·05	3·4	2·81	2·7	2·59	2·48	2·38	2·28	1·8	1·37	1·0	0·702	0·45
40	296	3·8	3·19	2·64	2·53	2·43	2·33	2·23	2·14	1·69	1·29	0·95	0·659	0·422
30	315	3·57	3·0	2·48	2·38	2·29	2·19	2·1	2·01	1·59	1·21	0·892	0·62	0·396
22	330	3·41	2·86	2·36	2·27	2·18	2·09	2·0	1·92	1·51	1·16	0·852	0·592	0·379

0·025 sq. in. copper

Basis:—

Radial ice = $\frac{3}{16}$ in.
Wind pressure = 8 lb./sq. ft.
Stranding = 3/·104 in.
Factor of safety = 2.
Breaking load = 1 517 lb.
Maximum span = 300 ft.

(17) OUT-OF-BALANCE IN TENSION

From Fig. 23 the extent of the out-of-balance in tension at an insulator at 122° F., due to differing span lengths on either side, may be readily determined. As mentioned above, the basis of calculation is the tensioning of conductors at 40° F., the temperature subsequently rising to 122° F. The peak of each tension curve indicates the tension at 122° F. for the basic maximum span and is the tension shown in the linesman's chart. For spans which are shorter than the basic span, the loss in tension is the difference between the readings for the span lengths under consideration.

Although it is common practice to ignore these small differences in tension, it is interesting to form some idea

Table 5

H.V./L.V. Construction: Linesman's Sag Chart

Size of conductor	Sag for various span lengths (in feet)											
	200	180	170	150	140	135	130	125	120	115	110	100
sq. in. 0·06	2′ 9¼″	2′ 3″	2′ 0″	1′ 6¾″	1′ 4¼″	1′ 3¼″	1′ 2″	1′ 1¼″	1′ 0″	11″	10″	8¼″
0·04	2′ 9¼″	2′ 3″	2′ 0″	1′ 6¾″	1′ 4¼″	1′ 3¼″	1′ 2″	1′ 1¼″	1′ 0″	11″	10″	8¼″
0·025	2′ 9¼″	2′ 3″	2′ 0″	1′ 6¾″	1′ 4¼″	1′ 3¼″	1′ 2″	1′ 1¼″	1′ 0″	11″	10″	8¼″

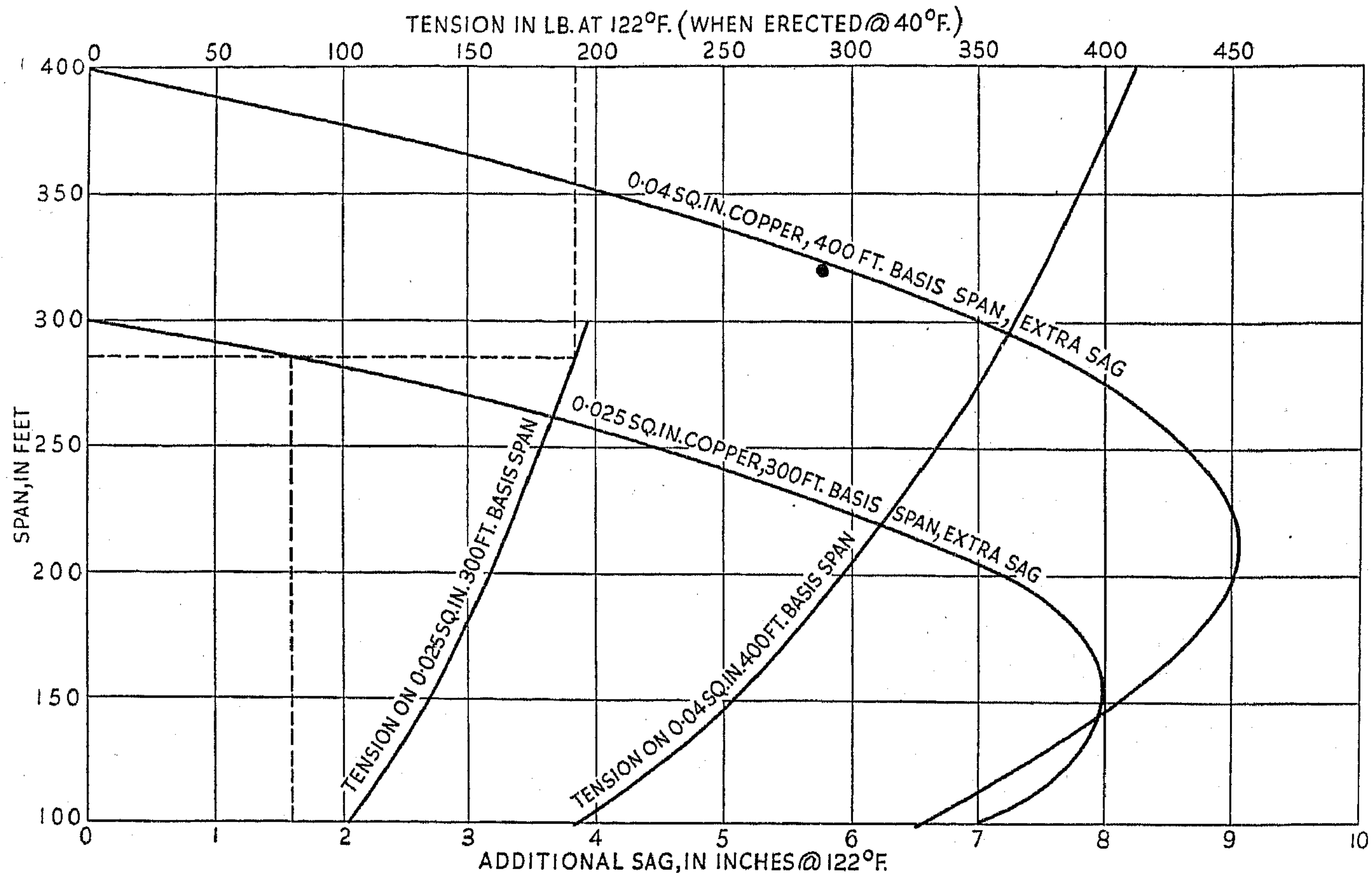


Fig. 23.—Sag tolerance and out-of-balance in tension, after binding-in at 40° F.

of the extent of the out-of-balance which has to be taken up by the binding at the insulator and the flexibility of the poles. It is only for this purpose that tension curves have been shown on the graph.

ductors instead of, say, 0·1 sq. in., owing to the ready installation of transformers when necessary, the total tension in a line is about the same for 3-phase h.v./l.v. as for 0·1-sq. in. 3-phase low voltage.

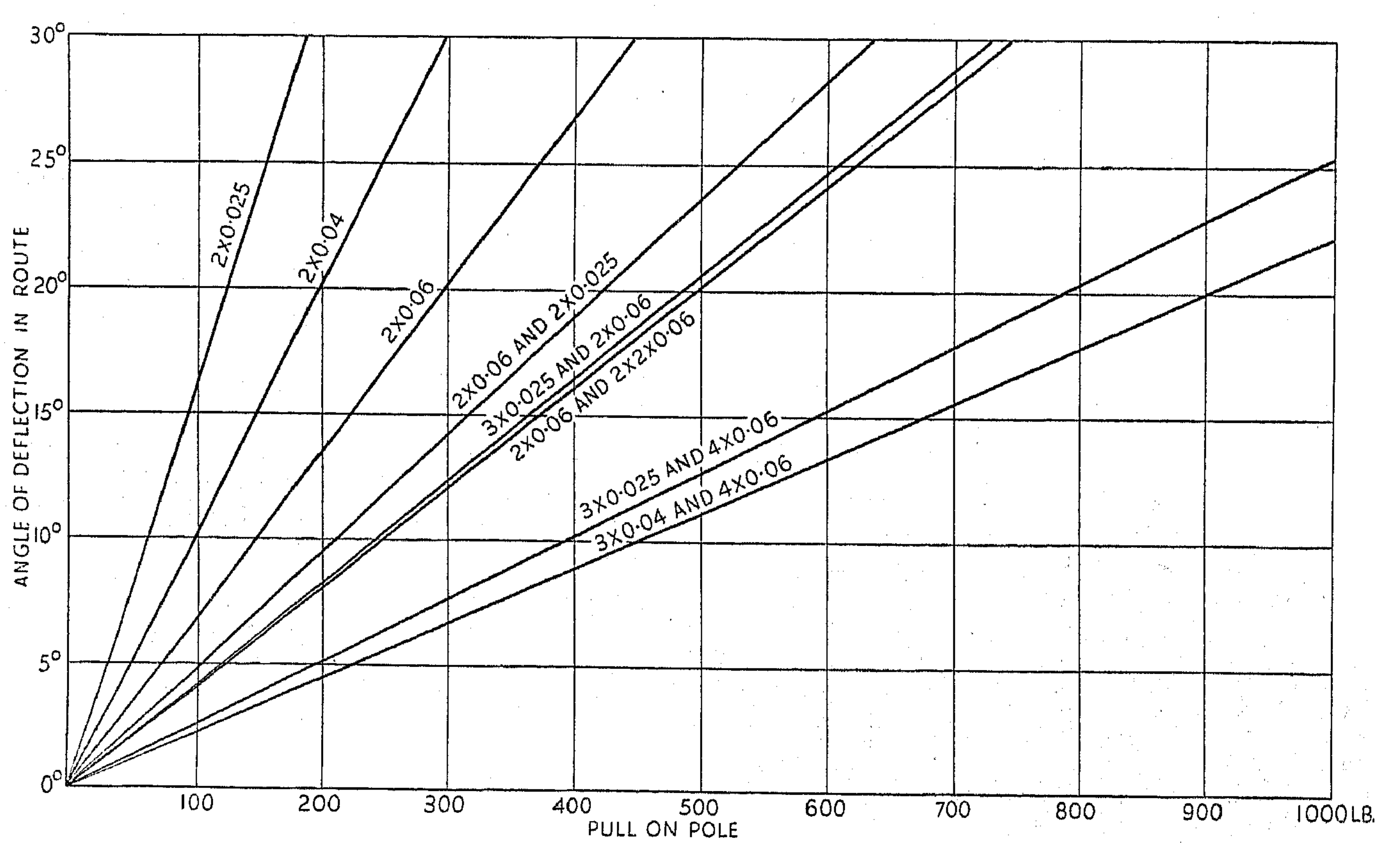


Fig. 24.—Pull at angle poles, h.v./l.v. distributors.
Basis:—1 ft. sag and 120 ft. span.

(18) PULL OF LINE DEFLECTIONS

The introduction of h.v. conductors on existing l.v. schemes makes it necessary to pay careful attention to the pull exerted by deflections in the line. For new schemes where it is possible to use 0·06-sq. in. l.v. con-

Fig. 24 shows the pull exerted by different conductors for varying line deflections when pulled up at 40° F. to linesman's chart (Table 5). This graph, when used in conjunction with the pole deflection graph (Fig. 25), is very useful for determining pole

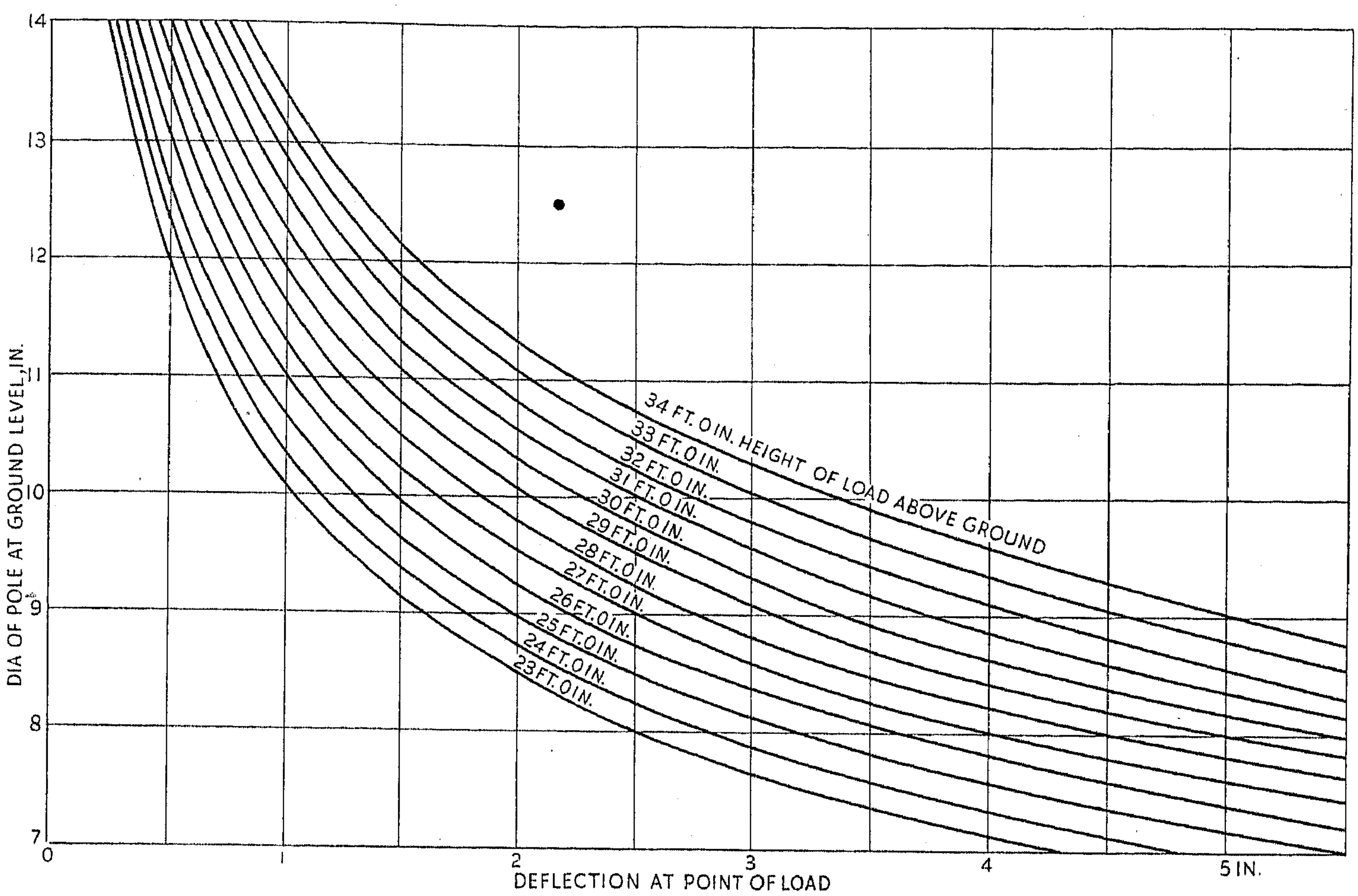


Fig. 25.—Wood (red fir) pole deflections for a load of 100 lb. cantilever.

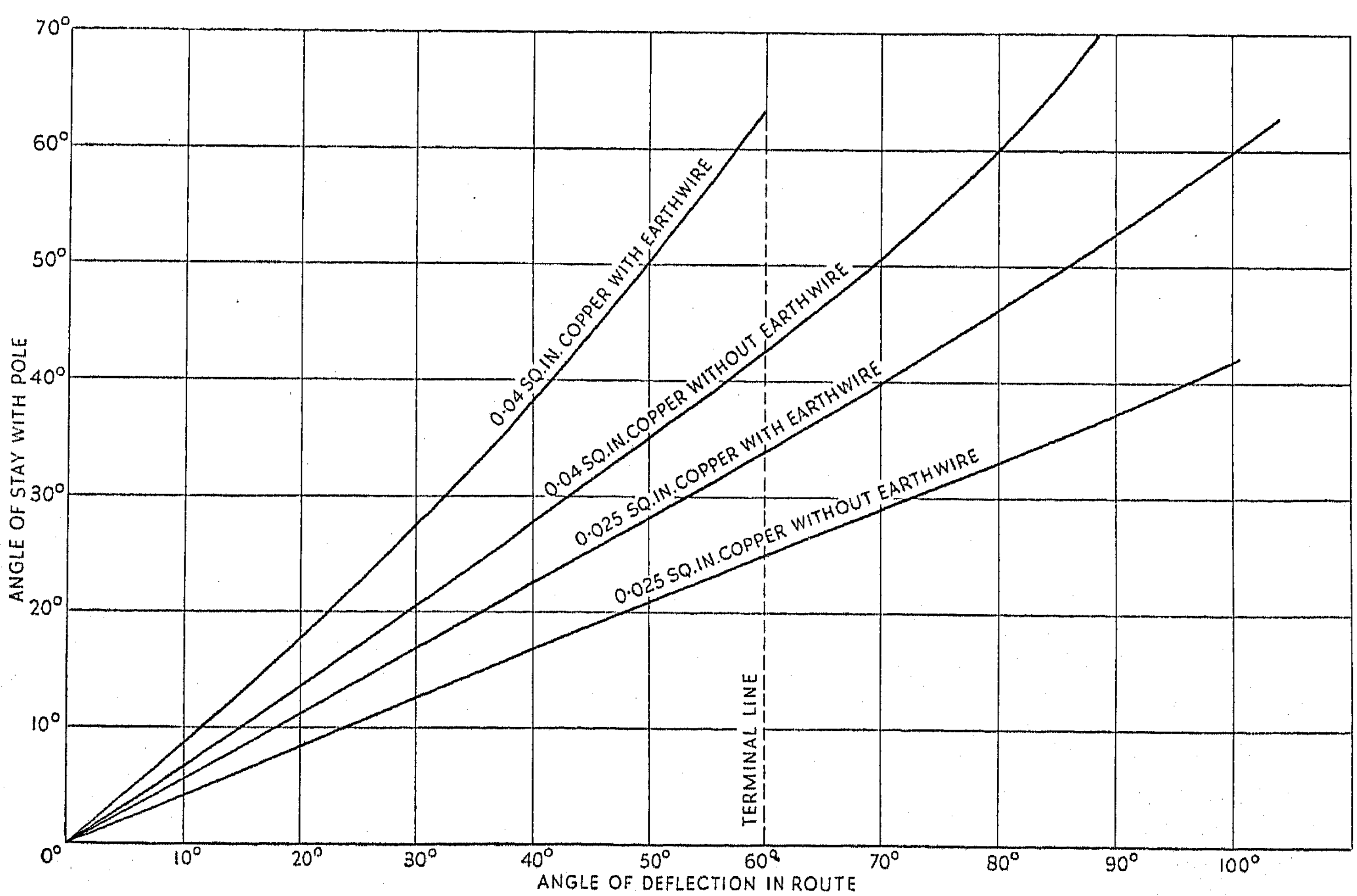


Fig. 26.—Angle of stay for one $\frac{7}{8}$ S.W.G., 45-tons quality stay.

sizes at slight angle positions where staying cannot be arranged.

(19) POLE DEFLECTIONS

Fig. 25 shows the extent of pole deflections per 100 lb. cantilever for poles of various lengths and diameters and is particularly useful on h.v./l.v. or low-voltage schemes only.

(20) STAYS

The standard practice on h.v. lines, of aiming to obtain an angle of 30° to 45° between the stay and the pole in order to restrict the crippling stresses, should be considered in connection with the light-construction lines described in the paper.

As conductor working or normal tensions are comparatively low for small copper conductors, it follows that the crushing load created by the stay or stays is considerably less under normal conditions than for heavier types of line. The real factor, however, is the necessity to have sufficient tension in the stay wire itself in order to obtain reasonable rigidity.

In the case of 0·025-sq. in. copper 11-kV 3-phase lines without a continuous earth wire, a stay made off at 45° would have to exert only 385 lb. at 60° F. in order to balance the line pull at an angle pole carrying a 20° line deflection. In order to give greater rigidity, the angle which the stay makes with the pole should be kept reasonably small so as to permit increased tension in the stay. This should be done to the full extent possible within the requirements of the Electricity Commissioners' Overhead Line Regulations.

Fig. 26 shows the minimum stay pole angle which may be used consistent with regulations for conductors of different sizes and various line deflections.

Pole sizes for the combined construction are calculated on straight-line basis and should be increased for unstayed line deflections and at positions where heavy services are to be taken off.

(21) PLOTTING POLE POSITIONS

Fig. 27 shows a special type of celluloid sag template designed with the object of speeding up work, and at the same time reducing the risk of errors in draughtsmanship. This template dispenses with the alternative single-curve celluloid template or the older method of moving a transparent profile sheet over conductor curves drawn on paper or linen and finally tracing off. It will be found preferable to use thin squared paper (from which prints can be obtained direct) as the profile medium, as this assists the surveyor when transferring readings from his log book and also enables the template to be used without employing other instruments for maintaining balance of the curve.

(22) POLE SIZES

It is common practice to determine pole diameters from pole-strength tables, but as this involves the calculation of wind load in pounds on each pole it is a rather laborious method. An alternative is the use of Tables similar to Tables 6, 7 and 8, which give the maximum loading span dealt with by any pole of given height and diameter. A Table of this type reduces the possibilities

Table 6

WOOD POLE (RED FIR) STRENGTHS. STRAIGHT-LINE SINGLE POLES (WITH CONTINUOUS EARTH WIRE)

Pole dimensions		Maximum loading space (in feet)			
Height above ground	Diameter	3—0·04-sq. in. conductors and 1—7/12 S.W.G. earth wire	3—0·025-sq. in. conductors and 1—0·025-sq. in. or No. 7 earth wire	3—No. 7 conductors and 1—No. 7 earth wire	3—No. 8 conductors and 1—No. 8 earth wire
ft.	in.				
25	7	123	133	145	149
	7½	158	171	186	191
	8	198	215	234	240
	8½	242	260	284	293
	9	292	315	343	353
	9½	350	376	409	421
	10	411	432	482	496
27	7	108	116	127	130
	7½	140	152	165	170
	8	177	192	208	214
	8½	217	233	254	262
	9	263	282	308	317
	9½	314	237	368	378
	10	372	400	436	448
	10½	435	469	510	525
28·5	7	98	106	116	119
	7½	128	138	151	155
	8	163	176	192	197
	8½	200	215	234	241
	9	243	260	284	292
	9½	292	312	340	350
	10	345	371	403	415
	10½	405	435	475	488
30	7½	117	127	138	142
	8	150	162	176	181
	8½	184	198	216	223
	9	225	242	264	271
	9½	270	291	317	326
	10	321	345	376	387
	10½	377	406	442	455
	11	441	474	517	532
32	8	134	145	158	163
	8½	166	179	195	201
	9	204	219	239	245
	9½	246	265	287	296
	10	292	315	342	352
	10½	345	371	403	416
	11	404	435	473	487
34	8½	151	163	177	182
	9	184	198	216	222
	9½	223	240	262	269
	10	266	287	312	321
	10½	316	339	370	381
	11	371	399	435	447
	11½	432	465	506	521
36	8½	135	146	159	163
	9	167	181	197	203
	9½	203	219	239	246
	10	244	263	286	295
	10½	289	311	338	348
	11	342	367	400	412
	11½	399	430	468	481
39	9	145	157	170	175
	9½	177	192	208	214
	10	214	230	251	258
	10½	255	274	298	307
	11	302	325	354	364
	11½	355	382	415	428
	12	412	443	482	486

Basis:—Loading point = 2 ft. from top.
Radial ice = $\frac{3}{16}$ in.
Wind pressure = 8 lb./sq. ft.
Factor of safety = 3½.

Table 7

WOOD POLE (RED FIR) STRENGTHS. STRAIGHT-LINE SINGLE POLES (WITHOUT CONTINUOUS EARTH WIRE)

Pole dimensions		Maximum loading span (in feet)			
Height above ground	Diameter	3—0·04-sq. in. conductors	3—0·025-sq. in. conductors	3—No. 7 S.W.G. conductors	3—No. 8 S.W.G. conductors
ft.	in.				
25	7	163	172	187	192
	7½	208	221	240	246
	8	263	278	302	311
	8½	322	341	370	381
	9	388	411	447	459
27	7	142	150	163	168
	7½	186	197	214	220
	8	235	249	270	278
	8½	290	305	334	343
	9	349	369	402	413
	9½	417	442	481	494
28·5	7	129	137	149	153
	7½	170	180	195	201
	8	215	228	248	255
	8½	266	282	306	315
	9	323	342	371	382
	9½	387	410	446	458
	10	458	486	527	543
30	7½	155	164	178	183
	8	199	210	229	235
	8½	245	260	282	290
	9	300	318	345	355
	9½	360	381	414	426
	10	428	453	492	507
32	8	178	188	204	210
	8½	222	237	255	263
	9	271	287	313	321
	9½	327	346	376	387
	10	390	413	449	462
	10½	461	488	530	545
34	8½	159	168	182	188
	9	245	260	283	291
	9½	298	316	343	353
	10	355	376	408	420
	10½	422	447	486	499
36	8½	179	190	206	212
	9	223	236	256	263
	9½	271	287	313	321
	10	327	345	376	386
	10½	386	409	444	457
	11	457	484	526	541
39	9	193	204	222	228
	9½	236	250	271	279
	10	286	302	329	338
	10½	340	360	391	402
	11	404	428	466	478
	11½	474	503	546	562

Basis:—Loading point = 1 ft. 6 in. from top.
Radial ice = $\frac{3}{16}$ in.
Wind pressure = 8 lb./sq. ft.
Factor of safety = 3½.

Table 8

WOOD POLE (RED FIR) STRENGTHS. COMBINED H.V./L.V. SINGLE POLES

Pole dimensions		Maximum loading span (in feet)			
Height above ground	Diameter	2—0·04 sq. in. 2—0·1 sq. in. 1—No. 8 S.W.G.	3—0·04 sq. in. 4—0·1 sq. in. 1—No. 8 S.W.G.	3—0·04 sq. in.	3—0·025 sq. in.
ft.	in.				
23	8	176	—	300	316
	8½	209	135	361	—
	9	—	162	434	—
25	8	153	—	263	278
	8½	187	120	322	342
	9	225	144	388	—
	9½	—	171	—	—
27	8½	167	—	288	304
	9	202	130	348	—
	9½	—	154	—	—
29	8½	150	—	258	274
	9	182	116	315	334
	9½	218	139	378	—
	10	—	164	—	—
30	8½	142	—	—	258
	9	173	110	300	318
	9½	208	132	360	—
	10	—	157	427	—
	10½	—	184	—	—
32	9	156	—	272	287
	9½	189	120	327	346
	10	—	143	390	—
	10½	—	168	—	—
34	9½	170	—	298	316
	10	205	130	355	—
	10½	—	154	421	—
	11	—	180	—	—
39	10	165	—	286	302
	10½	196	124	340	—
	11	—	146	404	—
	11½	—	171	—	—

Basis:—

Loading point:—

Col. 3 = 2 ft. 0 in.
Col. 4 = 3 ft. 0 in.
Cols. 5 and 6 = 1 ft. 6 in.

Radial ice = $\frac{3}{16}$ in.
Wind pressure = 8 lb./sq. ft.
Factor of safety = 3½.

of error, facilitates checking, and altogether easily repays the labour involved in its preparation.

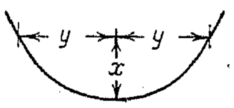
(23) WAYLEAVES

Although in some cases wayleaves may be more readily obtained on long-span lines, owing to the smaller number of supports employed, it also follows that it is not so easy to agree fixed pole positions or line deflections. This is due to the fact that on long-span lines an extra support creates a greater proportional increase in cost per mile of line than does an extra support on short-span lines. In addition to this, there is a rapid rise in cost when extra angle poles are introduced on highly stressed lines.

The annual cost of wayleave rentals is sometimes mentioned as a criticism of light-construction lines. This is not necessarily true, because the flexibility of the line produces the ability more easily to plan routes and follow where necessary hedgerows and fences, thereby obtaining wayleaves at first request, where objection may otherwise be made. This, in conjunction with the smaller number of stays required (the reduced spread is frequently helpful), generally counteracts the higher cost of rentals over arable ground.

Should particular routes offer wayleave rental benefits by the use of long-span steel lines instead of shorter-span copper lines, it should not be overlooked that any rental benefit thereby obtained is generally completely overshadowed eventually by the saving in annual cost of losses effected by using copper conductors.

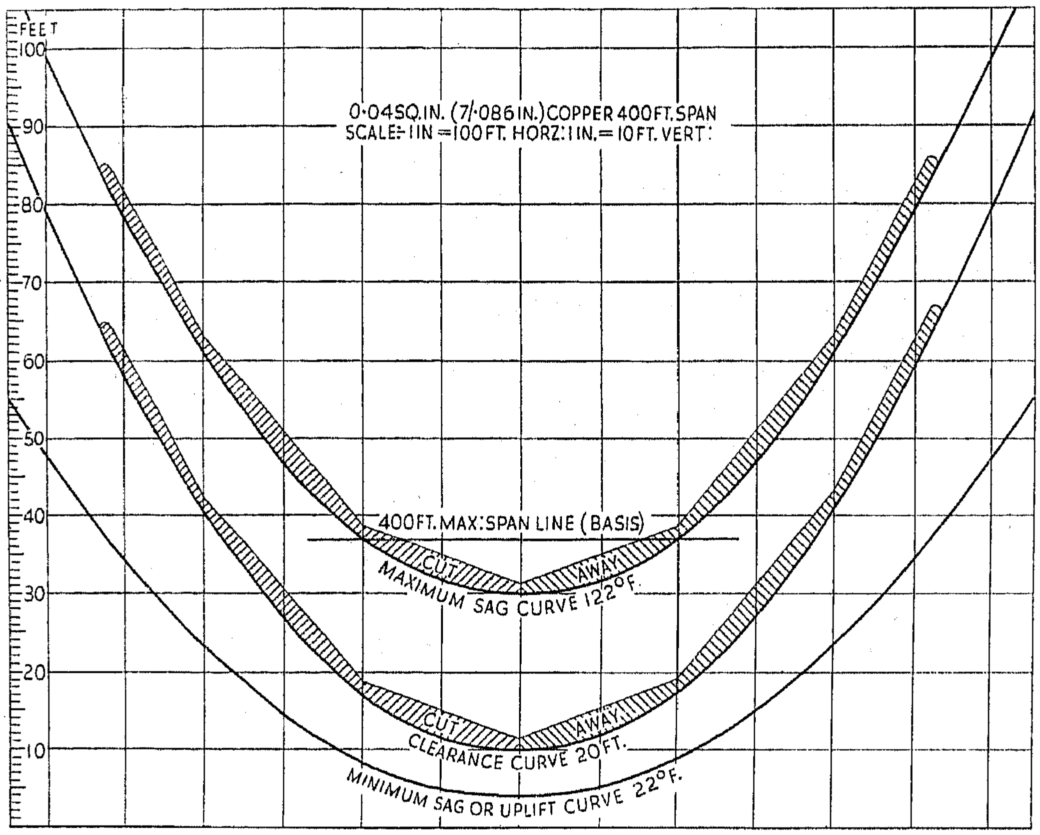
In the case of h.v./l.v. lines erected along roadways the wayleave problem is comparatively easy.

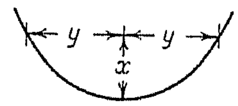


Maximum-Sag Template

Basis: $y^2 = 5\,162x$

y	x
50	0·485
100	1·94
150	4·36
200	7·75
250	12·11
300	17·33
350	23·73
400	31·0
450	39·22
500	48·45
550	58·6
600	69·75
650	81·83





Minimum-Sag Template

Basis: $y^2 = 8\,225x$

y	x
50	0·304
100	1·216
150	2·735
200	4·862
250	7·599
300	10·94
350	14·89
400	19·45
450	24·62
500	30·4
550	36·7
600	43·78
650	51·4

Fig. 27.—Celluloid sag templates. Scale: ⅓ full size (approx.).

CONCLUSION

An attempt has been made in this paper to deal with the question of rural h.v. distribution lines from general theoretical, practical, and financial standpoints, and against each of these it may be said that copper lines appear in a favourable light when compared with steel.

A survey has also been made of the possibilities in rural development which are opened up by the use of combined h.v./l.v. distribution lines, and in this connection the author would like to add a final word regarding comparisons between h.v./l.v. and l.v. only schemes, as it will often be found that the initial cost of a combined

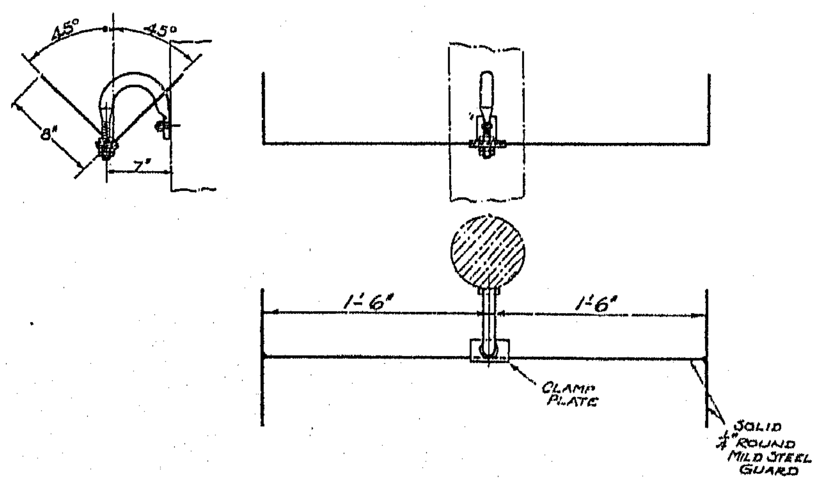


Fig. 28.—"V" type earth guard.

scheme, even after allowing for smaller l.v. conductors, is no less than for a standard l.v. scheme. Generally, where a single-phase h.v./l.v. scheme can be used instead of 3-phase low voltage the cost will be lower than for

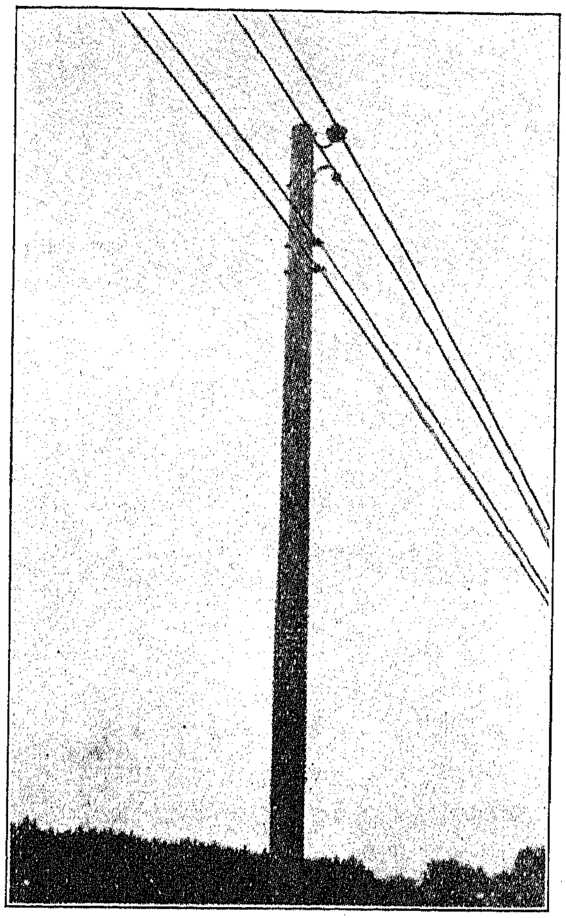


Fig. 29A.—Through pole. Single-phase high and low voltage.

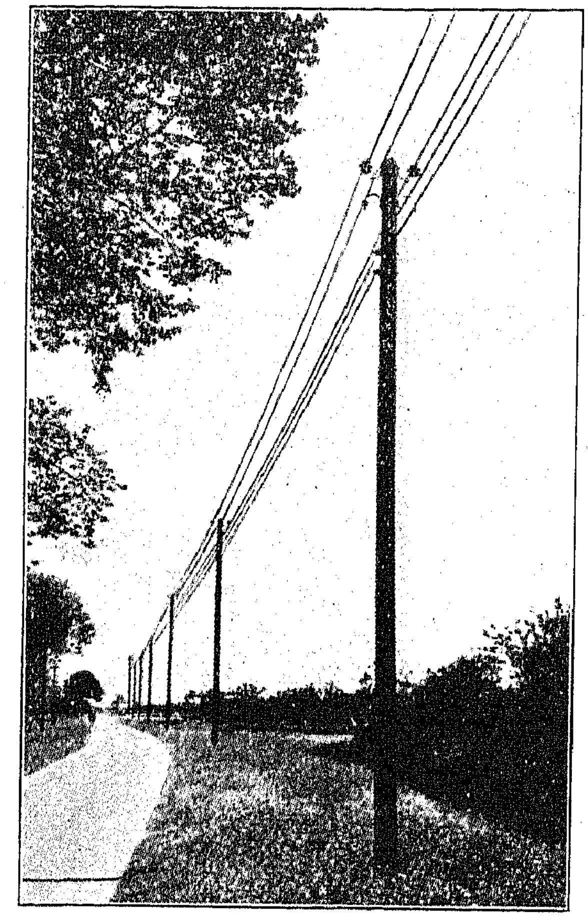


Fig. 29B.—Through pole. Three-phase high voltage and single-phase low voltage.

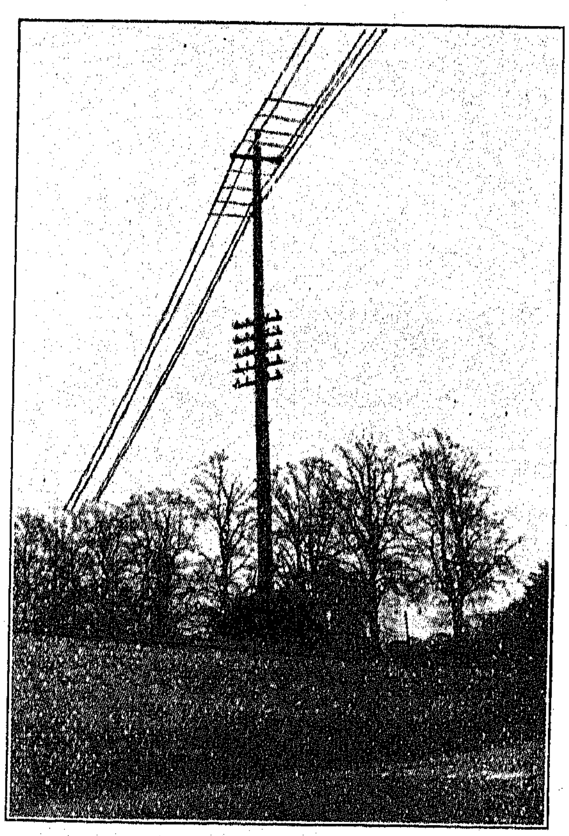


Fig. 29C.—Joint-user pole. Single-phase high and low voltage with P.O. line.

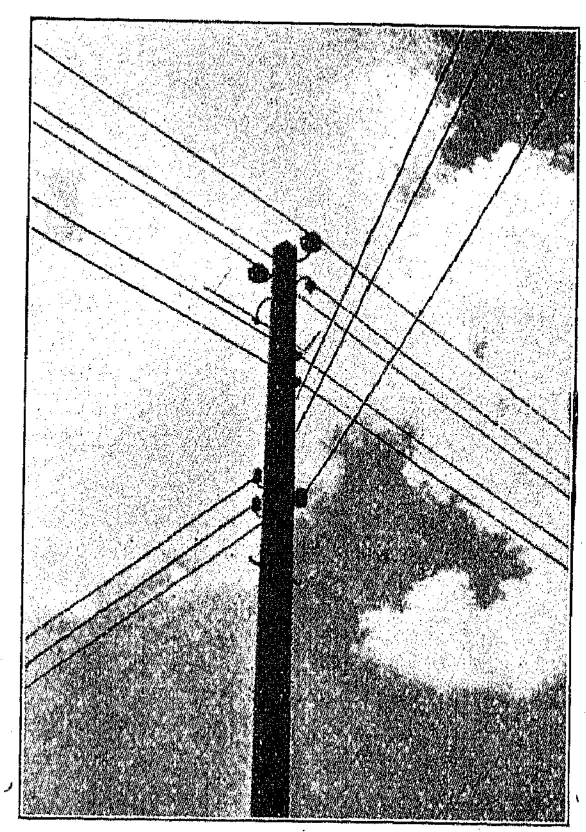


Fig. 29D.—Joint-user pole. Three-phase high voltage and single-phase low voltage with P.O. subscriber's line.

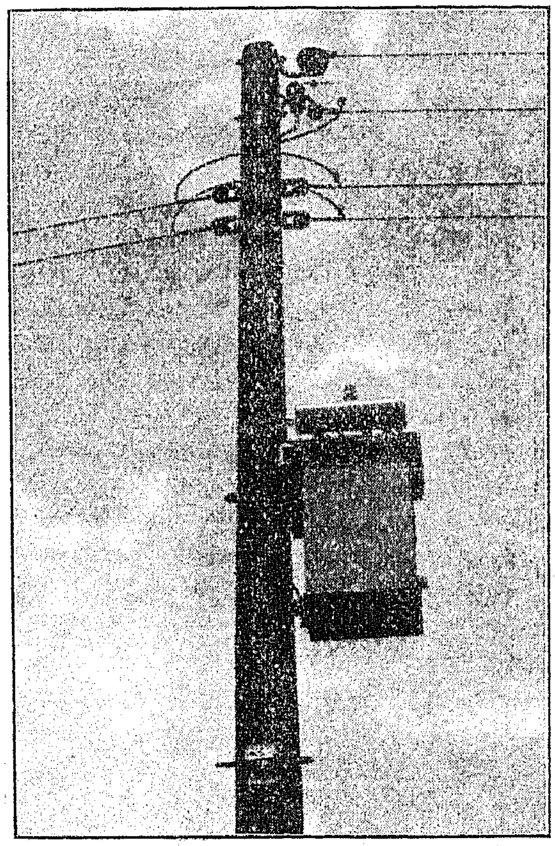


Fig. 29E.—Transformer pole. Single-phase h.v./l.v. construction.

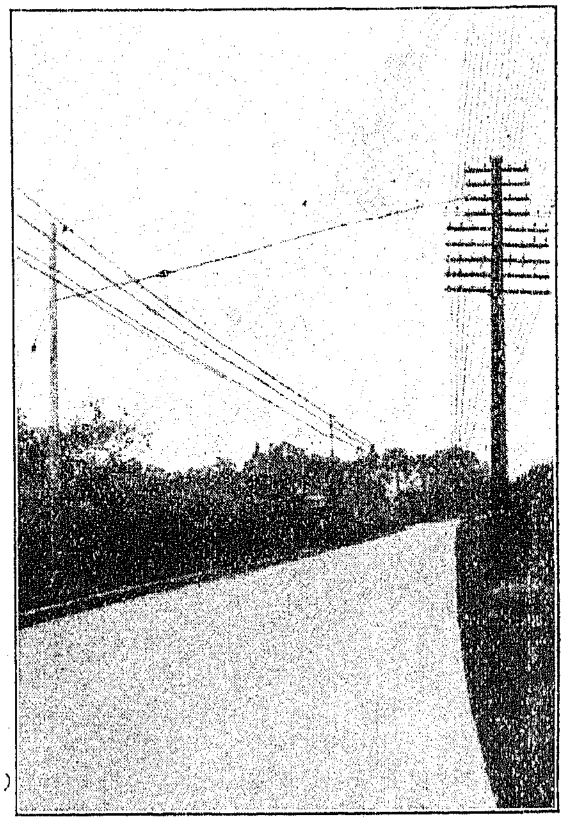


Fig. 29F.—Flying stay, P.O. line to power line. Single-phase high and low voltage.

the latter, but where 3-phase high voltage is necessary on a new or initial scheme there is sometimes little difference in cost. In cases such as the latter the greater scope of h.v./l.v. should be borne in mind, and also the fact that subsequent additions and extensions to the network can be carried out more readily and at less cost, particularly as this can often be done without changing the existing h.v./h.v. transformer.

In conclusion it may be said that the elimination of the use of steel conductors for h.v. lines in favour of copper, except in particularly special cases, and the successful development of combined h.v./l.v. networks, are factors which will, in the near future if not immediately, remove to some extent the difficulties and restrictions which in the past have proved a handicap to the full development of load in rural areas.

WRITTEN CONTRIBUTIONS TO THE GENERAL DISCUSSION ON THE ABOVE PAPER

Mr. P. B. Frost: The author gives prominence to certain relaxations from the standard requirements which have been made by the Post Office with a view to facilitating the construction of light h.v. and combined h.v. and l.v. lines in proximity to existing Post Office lines, and expresses his appreciation of these concessions in generous terms.

It may be said that every effort has been made by the Post Office to relax those conditions which presented special difficulties, without undue reduction of the margin of safety essential for the public telephone service. But it was necessary to make the reservation, fully covered in the memorandum E.-in-C.229, that the erection of these power lines along a road already occupied by a Post Office line must not prevent the running of telephone service lines across the road with proper clearance above the road and adequate clearance below the power line. To facilitate such crossings it has been agreed in principle that telephone service lines may be attached to the power poles. Unfortunately this concession does not always provide a solution free from drawbacks, as the required road clearance may involve the use of a taller power pole than would otherwise be needed, and a taller power pole necessitates a correspondingly greater separation between the two lines, so as to conform with the new overturning rule.

In view of the full co-operation between the Post Office and certain interested undertakers in finding the best solution to the difficulties encountered, it is hoped that power undertakers generally will not regard this condition as a hardship, because, if it had not been made, the Post Office would have been left with no alternative to providing underground services, and it is not part of the scheme described in this paper to develop cheap power lines at the expense of the public telephone service.

The reference at the end of Section (7) to duplicate insulation is somewhat obscure: if the intention is to provide for duplicate insulators by means of a double side bracket, the arrangement could hardly fulfil its purpose as the insulators would be in tandem instead of at right angles to the line, and in this position would afford no greater security from the risk of lines breaking away.

The concession made by the Electricity Commissioners in allowing power lines to be designed on the basis of a $\frac{3}{16}$-in. instead of a $\frac{3}{8}$-in. radial ice loading is nothing more than covering authority for the use of a lower factor of safety. Unfortunately, under certain atmospheric conditions, lines will become so heavily loaded and be sub-

jected to such wind pressure as to break, and presumably the Commissioners are satisfied to rely upon the protective apparatus to cut the power off promptly when this happens. It would be interesting to know whether any cases are on record where the use of self-reclosing circuit-breakers has resulted in a fallen line being left alive when it has come to rest in such a position as to make indifferent contact with earth.

The design of overhead telephone lines with a relatively large number of light-gauge wires is based upon the assumption that the worst conditions of ice and wind loading which occur from time to time in this country will inevitably cause serious failures. The problem is, however, an economic one and no question of danger to the public need be taken into consideration.

The earth bar shown in Fig. 5 has the advantage of performing the function for which it is provided without inviting bird trouble. The conventional form of earth bar provided on some 3-phase lines of 33 kV and above has, I think, brought earth bars into disrepute, since the most that could be expected of this form would be to earth the lowest conductor. It is an established practice for the Post Office to accept the l.v. neutral wire as the equivalent of an earthed guard wire, and for this reason it is particularly satisfactory to see that [in Section (10)] the author recommends that the l.v. neutral should be earthed to an electrode located outside the resistance area of that used for earthing the step-down transformer tank. This sound principle has too often been entirely ignored. It is not so clear, however, from Section (10)(*b*) how the transformer tank is to be earthed.* It could be earthed locally, or be connected to the permanently earthed h.v. conductor. Although neither course is really satisfactory, it would not be permissible to combine the two methods.

Nothing has been said by the author concerning the possibility of telephone interference. No trouble is anticipated from electromagnetic induction, but research is necessary to ascertain what danger or disturbance will arise from electric induction, particularly when the two lines run for several miles at a minimum distance apart and one or more wires on the telephone route are out of use, and therefore insulated at both ends.

With regard to the practical application of the turnover clearance rule given in E.-in-C.229, it is considered that curves such as those in Fig. 15 give rise to error through the need for interpolation. The specially constructed slide rule is interesting, but requires five operations.

For rapid computations, tables are preferred, but a possible alternative is the use of a 3-scale nomogram which requires a single operation to obtain the required result.

Mr. J. W. Gallop: One of the principal difficulties introduced by the h.v./l.v. system advocated in the paper is that in place of one single transformer a number are introduced, and therefore a number of adequate earths have to be made. As pointed out on page 43, the earth resistance should be low enough to allow at least twice the fusing current of the fuse. The smallest economical size of transformer on this system is about 15 kVA, single-phase, giving a full-load current of 65 amp. and requiring at least a 60-amp. high-rupturing-capacity fuse. Thus the smallest current required to clear the circuit on earth fault is 120 amp. Hence the total earth-fault resistance must not exceed about 2 ohms. I suggest that earthing at one point becomes economically impracticable in any but the most favourable soil. The undertaking with which I am connected found it necessary to apply for permission for multiple earthing. This was accomplished by earthing the neutral to 8-ft. rods driven to a depth of 10 ft. at about every other pole, depending upon the length of the l.v. line involved. By this means something approaching reasonably low values of earth resistance were obtained, and a means of giving adequate protection to such domestic apparatus as cookers, without the difficulty of supplying an adequate earth on the consumers' premises—there is no water supply in the village in question. Even so, it was found difficult to obtain a low enough value of earth resistance to allow a reasonably high value of l.v. fuse at the transformer.

I cannot quite understand why the h.v./l.v. system seems to have been designed primarily as a 3-phase system. Rural schemes do not involve power loads sufficient to justify three phases, and, in addition, three phases have to be balanced in order to obtain the full benefits of the increased capacity of the line as compared with single-phase distribution. The question of obtaining balance in a thinly populated rural area where loads are widely separated is usually an acute problem, and the chief merit of the h.v./l.v. scheme seems to be that its flexibility overcomes this difficulty without recourse to balancers, regulators and the like. The maximum voltage allowable, namely 6·6 kV, gives a load capacity* to most lines that should be sufficiently ahead of development to render other provision unnecessary. I appreciate that the h.v. lines must necessarily be 3-phase under some circumstances, but I should appreciate the author's views as to the practical economics of 3-phase l.v. distribution when used on this scheme, compared with single-phase.

Mr. T. Kearns: I agree with the author that the added interests of all the parties concerned in urging development in thin areas present a serious problem, especially in view of the normal time-limit of 2 years for a Special Order. Any method of construction which will effect reductions in capital outlay is therefore very welcome.

It is agreed that single-phase schemes will be found to satisfy a large proportion of small rural networks, as in such cases the balance of single-phase loads on a 3-phase 4-wire supply is not very effective. Also, owing to the increased possible diversity, a smaller distribution transformer should suffice for a single-phase system. No trouble should be experienced in connection with the use of single-phase motors for normal farm duties, although they are dearer in first cost. Single-phase 3-wire schemes for combined lighting and power loads, which are favoured in some areas, are not mentioned by the author. Does he find that the increased availability of h.v. feeding points renders such schemes unnecessary?

The method of supply suggested in the paper is to employ a normal 3-phase h.v. transmission ring supplying the various sections of h.v. lines through single-phase or 3-phase step-down transformers, with the h.v. secondary earthed on one side for the single-phase systems, and on the red phase for the 3-phase networks. As the concession regarding bonding of the steelwork of h.v. supports

* A correction has been made for the *Journal*.

is apparently only allowed where one of the wires is earthed, does this mean that all single-phase h.v. spur lines from a 3-phase network will have to have the red phase as one of the two conductors? Is there any difficulty in balancing the load on the 3-phase h.v. supply with this system; also, is much disadvantage found in the inability to parallel l.v. sections supplied from single-phase transformers off different h.v. phases?

The reference to radio interference caused by stranded-core cable is most interesting, and perhaps the author will supply further details.

Fig. 22 is very useful, but care must be taken in applying it, in any particular instance, as the cost of giving supply by means of a l.v. extension must be debited with the additional losses on the existing transformer (which may have to be increased in size). If this is allowed for, then a true comparison can be obtained by the use of Fig. 22.

Mr. F. P. Meadows: The concessions obtained for the h.v./l.v. design are for a maximum voltage of 6·6 kV to earth. Would it not be possible, therefore, to pursue the idea to its logical conclusion by running 11-kV and l.v. lines on the same poles? Most of the requirements given for the ideal rural line would thus be met in greater degree, and greater efficiency would result from only one stage of transformation and from the increased line voltage. Providing the 11-kV neutral is earthed, this would appear permissible, although the transformer substations might present some difficulty. Often it is the cost of the transformer substation as much as that of the line which restricts the possibilities of supplies to isolated points, and if this disability could be mitigated in some degree, further scope would be obtained for development in the thinner areas.

The load of 100 kW, quoted on page 44, is a comparatively high figure for small spur lines, and in such instances, when mechanical considerations rather than an application of Kelvin's law decides the choice of conductor, is the author prepared to recognize the claims of steel?

I am of the opinion that wayleaves are always more readily obtained for long-span lines, and with these the need for agreeing fixed pole positions is less. More often than not, advantage cannot be taken of the fact that short-span lines can be run along hedgerows, owing to the presence of trees, the felling of which may constitute a greater obstacle than opposition to the siting of poles in an open field. Furthermore, short spans tend to make a line more conspicuous.

It is not clear why 3 000-lb. swan-neck brackets are recommended for all section points. During conductor stringing it is not necessary to apply unbalanced line loadings to the swan-neck brackets of straight-line section poles, and if a conductor breaks in service it is usually found that the binding relieves the section pole of the resulting unbalance. Even so, the 3 000-lb. swan-neck bracket illustrated in Fig. 9, with its standard shank diameter, appears to have no extra strength in this direction, and its usefulness seems to be confined to angle and terminal positions.

Mr. H. Payn: The company with which I am associated has erected many miles of single-phase 3·3-kV combined lines using the construction shown in the left-hand illustration of Fig. 6, with the exception that a soft copper clamp was used in all straight-line and slight-angle positions for the earthed h.v. conductor. This was found to be cheaper than a bobbin insulator and the additional bonding at each pole. Has the author any objections to this form of fixing that can be substantiated in practice?

The new turnover regulation of the Post Office Engineering Department is a great boon, but even so it is found in South Lincolnshire that many country roads are not wide enough for both parties to have poles on the highway. As the law stands, compulsory wayleaves cannot be obtained in private gardens; thus construction is complicated or underground cable becomes necessary when the occupier proves obdurate. Tact in negotiating wayleaves may overcome most initial difficulties, but the occupier is in a very powerful position and, if he knows it, may bargain for extortionate terms. Has the author experienced any great difficulties in this respect?

Mr. F. W. Purse: Dealing first with the question of conductors (page 33, col. 2), copper-cored steel lines have adequate capacity for rural loads if the length is comparatively short and the loading not too heavy. I have submitted for the author's inspection a typical voltage chart taken over a period of 8 days, 16th–23rd May, 1938, on a voltage recorder fixed at the end of a line $3\frac{1}{2}$ miles long with 470 kVA of transformers connected along the route, which passed close to large brickworks. The chart shows that the extreme voltage variation during that period was 222–237 volts. The conductor in this case was 1/12 S.W.G. copper plus 6/12 S.W.G. steel; the line had spans of 400 ft. (average), and a conductor spacing of 4 ft., and was designed for a maximum span of 525 ft.

This type of line demands short spans, a fact which adds to wayleave difficulties and also to rentals. It is not always possible to follow hedge-lines, and the extra poles in fields would not be permitted. If hedge-lines are followed, additional route lengths and also extra angles are involved, adding to the cost per mile. In Table 2, spans of 300 ft. are recommended for 0·025-sq. in. copper conductor; the design gives 2 ft. 9 in. spacing. We find this insufficient to avoid conductors clashing, a contact having occurred on this spacing on a 200-ft. span, causing conductors to burn through.

It is difficult to see how a copper line, having short spans, can be as cheap as a steel line with long spans, as roughly twice as many poles are required, together with fittings and insulators, and the conductors are approximately $1\frac{1}{2}$ times as costly.

As regards the question of inconspicuousness (page 38), in our experience in Surrey, considerably more trees are met with in hedgerows than in open fields; also the felling of trees meets with strong opposition.

Turning to Fig. 19, where the load is very light the difference between steel and copper conductors as regards annual cost of losses is not so important as in other cases. Steel is generally used for lengths up to 1 mile and loadings up to 100 kVA, and for these figures there is only £2 per annum difference between 7/12 S.W.G. steel and 0·025-sq. in. copper. This is counteracted by the increased wayleave rents necessitated by more poles, involving additional annual expenditure. No mention is

made by the author of the losses with 7/12 S.W.G. copper-cored steel, which gives improved conductivity and greater mechanical strength.

Mr. R. B. Rowson: It is satisfactory to note that the fallacy of using steel conductors, except in exceptional circumstances, is becoming more widely realized. Nevertheless, the statement on page 45 that it is "sound economics to build a 0·025-sq. in. copper line even should the cost be £50 per mile higher than for 7/14 S.W.G. steel" needs qualifying. The statement is only true if we have 100 kVA-miles to transmit. Often the load is 10 kW and the distance, say, ½ mile; perhaps the supply is to one house. In such a case, if the total cost and the annual cost with steel are both appreciably less than with copper—which is often the case—a steel line is justified.

In Fig. 1, should not the bolts holding the top fitting be at right angles to the position shown? For a straight-line pole, most of the load is at right angles to the direction of the line. As shown, this load is all taken on bolts which tend to split the pole (cf. Fig. 6, in which the bolts are, perforce, in the correct position).

In the left-hand illustration of Fig. 3 the top jumper would, I imagine, be rather unstable. The other day I noticed one of these poles fitted with a jumper insulator on the top. Is this often necessary?

To reduce further the cost and increase the impulse flashover value of the construction shown in Fig. 1, the earth wire and all earthing of the ironwork might be dispensed with. Has the author considered this point, or is he awaiting the results of the E.R.A. investigations? The absence of the earth connection would also reduce the possibility of failure due to bird contact.

One difficulty which the author does not mention and which arises when a high-voltage system is operated with one phase earthed (or a single-phase system with one leg earthed) is that, in the event of the earthed wire breaking, the remote end is still fed via any transformer beyond the break and thus may rise to line voltage above earth. Owing to the high impedance of the circuit, the fault current is usually too small to blow the fuses. Has the author discovered any method of overcoming this difficulty. A further great disadvantage of earthing one phase of a 3-phase system which is not mentioned by the author is that it rules out the possibility of using a Petersen coil. In view of the advantages of Petersen-coil working* it would appear that this point is of some importance.

I do not agree that the capacity of a single-phase system is one-half that of a 3-phase system. On the basis of the last line in Table 1 the capacity of a 230-volt single-phase 0·1-sq. in. 2-wire system is 2·1 kVA-miles (1/6th of the value for the 3-phase case), while that of a 460/230-volt 3-wire single-phase system is 8·6 kVA-miles (2/3rds of the value for the 3-phase system).

The figures in Table 1 clearly indicate the advantage of raising the voltage to obtain increased capacity. Whilst there is a 66 % gain in capacity by following the author's suggestion of using 0·025-sq. in. copper conductors at 6·6 kV instead of 7/14 S.W.G. steel at 11 kV, a further gain of 280 % may be effected by increasing the operating voltage of the copper from 6·6 to 11 kV. In view of this, would the author state whether he considers that the Commissioners' restriction of the new proposals to 6·6 kV is necessary, and, if so, why?

It is disappointing that the author does not quote actual material and erection costs for the lines described, and I hope that he will do so in his reply.

Though the author rightly stresses the advantage of a single-phase h.v. system with 460/230-volt transformers, he does not mention the difficulties which arise due to the increased cost of single-phase motors. It must also be remembered that the number of kW which can be transmitted per £ of capital expenditure is much greater for a 3-phase system having conductors of the same size.

From Fig. 16 it appears that no fuses are used on either side of the 6 600/400-volt or 6 600/460-volt transformers. In the event of a fault such a procedure would lead to an extension of the area affected, and it may not be strictly in accordance with Sections 13 and 21 of the 1937 Regulations. There is also some difficulty in locating faults if several transformers are connected to the same line.

It is not clear why sections of the l.v. network should not be interconnected by suitable fuses. To do so reduces the voltage drop at points adjacent to what would be the far ends of the two separate systems and also materially reduces flicker.

Finally, as the purpose of the construction described is to reduce costs as much as possible, why are the transformers shown in Figs. 16 and 29E fitted with conservator tanks?

[The author's reply to this discussion will be found on page 58.]

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 16TH JANUARY, 1940

Mr. F. H. Whysall: The author's problem is to keep down capital expenditure and to give reliability and low maintenance cost. In my opinion the use of copper conductors is to be preferred, even if only on account of the high scrap value of copper.

I should like to know why the author recommends swan-neck brackets. Fig. A shows a cross-arm, usually described as the wish-bone type, which has been adopted in the Belfast rural district and is there considered to be superior to other designs.

While there should be sympathy with the author's desire to effect economy by using combined high-voltage and low-voltage distribution, as shown in Fig. 5, there would appear to be very few circumstances in which this type of construction could be made use of.

The adaptation of existing l.v. pole lines to carry superimposed h.v. lines, as shown in Fig. 6, does not appear to be a very practicable or satisfactory method of dealing with the problem. Alterations are always expensive, and experience in the Belfast rural area would appear to suggest no circumstances in which this method of construction would be an advantage.

On page 39 it is stated that the pole steps are fitted at

* See H. W. Taylor and P. F. Stritzl: *Journal I.E.E.*, 1938, **82**, p. 387.

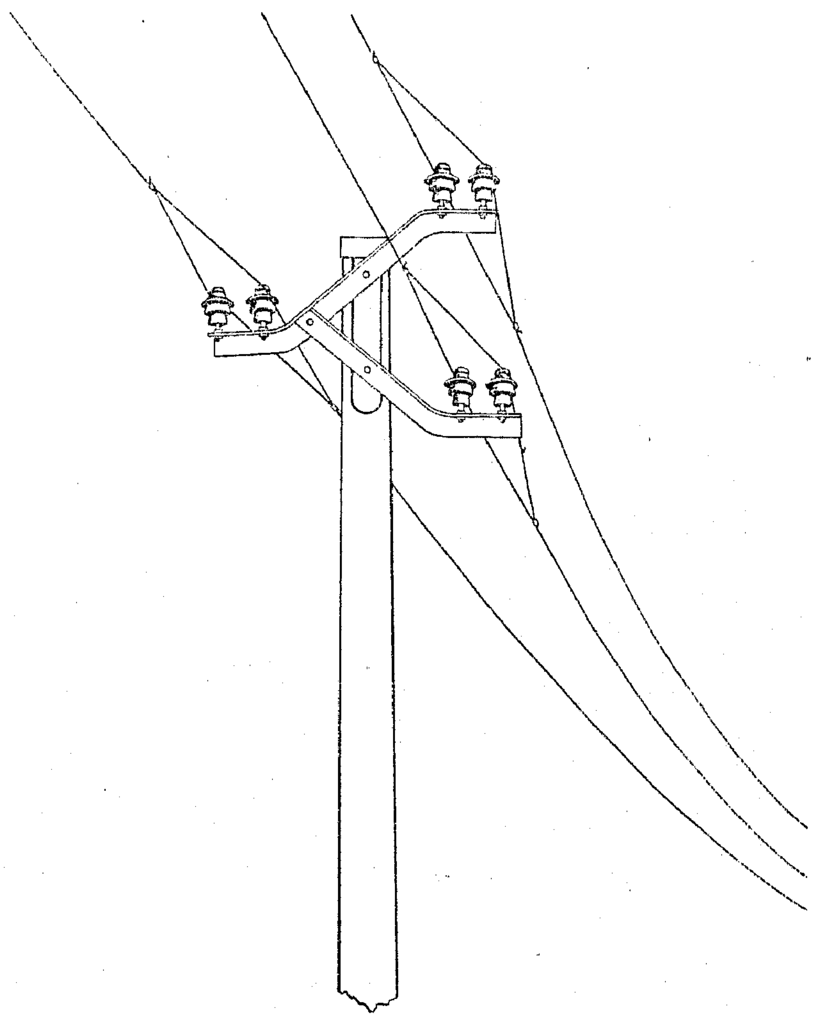


Fig. A.—Typical arrangement of double insulation on wishbone cross-arm.

a point of 6 ft. below the highest l.v. conductor, and that this has been done at the request of the Electricity Commissioners in order to minimize the possibility of a linesman going too high up the pole and making accidental contact with a live h.v. conductor. It would appear that linesmen would have difficulty in working on the highest l.v. conductor from this position.

The decision to allow reduced ice loading on small conductors is certainly a step in the right direction, but experience has proved that certain weather conditions cannot be provided for and that quite expensive lines of strong construction fail under weather conditions that can provide bad ice loading. In the North of Ireland steel pylons have been brought down through ice loading, and incredible damage has taken place.

I agree that it is practicable to dispense with kicking blocks for poles up to 36 ft. long (overall) and 120-ft. spans in ordinary ground, but I do not see any very great practical advantage in using small conductors. Practical experience shows that it is necessary to standardize one size of l.v. distributor, and in the rural districts round the city of Belfast 7-strand 0·1-sq. in. low-voltage and 3-strand 0·05-sq. in. high-voltage conductors have been standardized.

Anyone interested in this subject would do well to read the Rural Electrification Section of the *Transactions* of the 1938 World Power Conference in Vienna.

The Ministry of Commerce for Northern Ireland has taken an official interest in the question of encouraging, and reducing the costs of, the distribution of electricity to the farms in rural areas, but, so far as I know, nothing has been published with regard to their deliberations.

THE AUTHOR'S REPLY TO THE GENERAL DISCUSSION AND TO THE DISCUSSION BEFORE THE NORTHERN IRELAND SUB-CENTRE

Mr. K. L. May (*in reply*): I agree with Mr. Frost that there is no intention to develop inexpensive power lines at the cost of the public telephone service, and I would add that certain benefits operate to the mutual advantage of both the telephone and the electricity supply services —for instance, the attachment of telephone service lines to power line poles, and vice versa.

As most overhead low-voltage distributors are erected to provide statutory road-crossing clearance for any future service lines which may be taken off, the clause in the Post Office Regulations is not a serious imposition and should not occasion any concern on the part of supply authorities.

Detailed information regarding duplicate insulators is not given in the paper because standard methods are common knowledge, but, in answer to the point raised, the additional protection afforded against a conductor breaking away will be appreciated if I mention that arcing horns and a bridle wire are provided in addition to the duplicate insulators.

I do not know of any case where the employment of self-reclosing circuit-breakers has resulted in a fallen wire being left alive. Cases have, of course, been recorded of fallen lines controlled by means of manually reclosed circuit-breakers being alive whilst on the ground. In this respect there is no difference in the way the two types of circuit-breakers are normally operated in practice.

It may be of interest to record that during the exceptional blizzard of January last the performance of light construction lines designed on a basis of $\frac{3}{16}$ in. radial ice loading was most satisfactory and compared favourably with heavier construction lines with pin insulators. This experience tends to confirm that the Electricity Commissioners did not err when permitting the reduced loading of $\frac{3}{16}$ in. radial ice to be used as a basis in line design for small conductors up to and including 0·04 sq. in. copper. This, of course, constitutes in effect a reduction in the factor of safety, but, as explained in the paper, small conductors suffered a disadvantage under the original regulations and Table 2 was prepared partly to indicate the correctness of the decision to employ the lower loading figure.

In Section 10(*b*) the reference in the advance copies of the paper should have been h.v./h.v. instead of h.v./l.v. transformer. This correction has been made for the *Journal* and will clear the question of earthing of this unit. It would not be permissible to connect the earth of h.v./l.v. transformers to the earthed h.v. conductors, as that would in effect bring about multiple earthing of the h.v. system.

The possibility of telephone interference is being

carefully watched, and it is pleasing to report that no interference has yet been experienced although power lines have run for more than one mile parallel with the telephone route.

The problem of determining turnover clearance by the use of a 3-scale nomogram was the first method of attack, but I was unsuccessful in applying this method, hence the production of the curves and slide rule.

Mr. Gallop calls attention to the question of earthing. In reply I should like to say that, after many experiments to determine a convenient and reasonably effective method of earthing, it was found that the driving of earth rods vertically produced very unreliable results. Increasing the depth or length of rod to 8 ft. or 10 ft. did not necessarily improve the resistance to any marked degree. A more satisfactory earth is obtained by burying bare copper wire under the surface of the ground at a depth of 15 in. to 18 in. It is true that to increase the number of transformers employed thereby increases the number of earths, but this has no marked effect on the economics of a combined h.v./l.v. scheme.

I cannot agree that a 15-kVA transformer is the smallest economic unit to employ, because there is no reason why a 5-kVA transformer should not be installed if an isolated consumer is obtained on a section of the h.v. network which may be devoid of l.v. conductors owing to open country or absence of consumers in that section. In the U.S.A. I believe they standardize as low as $1\frac{1}{2}$ kVA for transformers on networks similar in type to those described in the paper.

I agree with Mr. Gallop that the provision of satisfactory earthing has inherent difficulties, but this is of course true to some extent of all distribution systems. I have referred above to the error in Section 10(*b*).

The h.v./l.v. system is not designed primarily for a 3-phase scheme but is so drawn up that it becomes readily applicable either for 3-phase or single-phase. In Section (3) I have stated that "single-phase schemes will be found to satisfy a big proportion of small rural networks" and Section 7(*h*) under the heading "Type of system" contains the views which are asked for by Mr. Gallop. This is confirmed by the fact that 3-phase schemes represent less than 2 % of the total completed to date.

Mr. Kearns raises the question of single-phase 3-wire schemes, and I am able to confirm that up to date it has been found that the increased availability of h.v. feeding points has eliminated the necessity to increase the l.v. system to 460/230 volts 3-wire. It may, however, be of interest to mention that h.v./l.v. transformers of 15 kVA and larger have been made with l.v. series/parallel windings so that any single-phase l.v. system can be readily changed to single-phase 3-wire should future demands warrant this step.

Where it is desired to split a 3-phase network of an h.v./l.v. scheme into single-phase spurs it is not essential in every case to use the red phase as one of the two conductors, although if balance can be obtained with this method on the 3-phase system it is preferred in order to restrict cost. The alternative is to run two conductors and a continuous earth wire, the latter being the red phase, which in this case would be used for bonding and guarding purposes only. The necessity for this has only arisen once in approximately 100 schemes so far completed.

Lead-covered cambric-insulated stranded-core cable was used in the first scheme which was energized at 3 300 volts, and radio interference was not experienced, but with 6 600 volts a certain amount of interference was caused. Experiments carried out in conjunction with the cable manufacturers proved the interference to be due to the inherent features of the cambric insulation. The remedy was paper insulation and, to a far smaller extent, a solid core, and this has proved quite satisfactory.

Mr. Kearns is correct in saying that the cost of giving a supply by an extension to the l.v. mains must be debited with the additional losses on the existing transformer. As the transformer copper-losses only are affected, and as these vary according to the position in the curve taken by the additional load to be imposed, it was impossible to allow for this in Figs. 21 and 22.

Mr. Meadows suggests that line voltage should be increased to 11 kV, but in the early stage of negotiations the authorities would not consent to a higher voltage than 6·6 kV. Subsequently this was amended to 6·6 kV to earth, so that it is already permissible to employ 11 kV provided the star point is earthed. Experience with 6·6-kV systems has, however, proved that for rural Britain this voltage is economic and, what is very important, permits of neatness in design.

It is only the smallest of schemes fed direct from existing 11-kV networks which prove more economical than when the voltage is stepped down to 6·6 kV. One further point in favour of standardizing 6·6 kV is that h.v./h.v. transformers must be incorporated where combined schemes are fed from 33-kV networks, and step-down to 6·6 kV is economic. In view of the increasing use of 33-kV lines this point is not unimportant.

As the scope of the paper extends far beyond small spur lines the criticism of the example of 100 kW quoted in Section (13) is not relevant. The last paragraph of the paper contains a reference to the possibility of special cases occurring where steel conductors may be justified, and presumably it is a case of this type which Mr. Meadows has in mind.

Actual tests have proved that the 3 000-lb. swan-neck (Fig. 9) when sunk into the pole in the manner described provides the requisite additional strength and allows for sectioning off direct if this manner is preferred. Although it is agreed that sectioning can be carried out without unbalanced load in the case of short lines, the balanced-load method is recommended. As it is not always practicable to finish conductor stringing at a terminal pole during the construction of a line, the inclusion of heavy swan necks at section poles eliminates the risk of its having to be done on a swan neck which is not adequate for the purpose.

It is pleasing to learn that Mr. Payne has erected many miles of 3·3-kV single-phase combined lines, presumably with satisfactory results, as no qualifications have been made, and I am confident of its continued success. I agree that h.v./l.v. construction cannot be applied to every scheme which may justify its use, as cases sometimes occur where, as Mr. Payne mentions, telephone lines exist on routes which cannot be made to provide the requisite clearance for both telephone and power lines.

In particularly difficult cases it may not be possible to employ economically a combined h.v./l.v. system of distribution, but fortunately these instances do not occur very often.

There is no objection to the use of a copper clamp for securing the earthed wire, provided the design eliminates the risk of abrasion and damage to the conductor.

Mr. Purse draws interesting comparisons and calls attention to the possibilities of copper-cored steel, which is admittedly a step in the right direction away from steel conductors. The use of composite conductors of this type is brought about by an attempt to maintain long span construction and at the same time obtain some part of the aditional capacity offered by a copper line. In certain circumstances a good case can be made out for copper-cored steel conductors on a particular scheme. Assuming in the scheme quoted that 470 kVA is the maximum load, the cost of line losses is roughly 60 % greater than would have been the case if 0·025 sq. in. copper conductors had been employed. Fig. 19 gives this additional loss as £10 per mile of line, or £5 per mile of distributed load. As these losses are chargeable to revenue account and will increase as the square of the load, a definite burden is imposed unless first costs are low. Should it be necessary to extend the line in the future, or to connect additional consumers, then the greater capacity offered by copper conductors and the resultant saving in losses would probably justify copper in the first instance.

The reference to span length illustrates to some extent the statement made in Section (23), because the line now in question was designed for a maximum economic span of 525 ft. and yet the average actual span was as low as 400 ft.

Table 2 was prepared primarily to assist in proving the correctness of the Commissioners' decision to permit reduced loadings as a basis for small conductors, and it should not be read as a recommendation regarding actual span lengths.

Reference to Table 4 indicates a sag of 1·9 ft. for a 200-ft. span and a tension of 262 lb. at 60° F. for 0·025 sq. in. copper when erected to a 300-ft. span basis chart. I can confirm that 2 ft. 9 in. spacing is perfectly satisfactory and has been proved over many miles of line. Presumably, therefore, the particular line to which reference is made was built either before, or without taking advantage of, the Electricity Commissioners' circular letter M.2854, in which case the tension in the conductors would only be 120 lb. and the sag would be 4·2 ft., a very different condition from the 262 lb. and 1·9 ft. sag referred to above.

Mr. Purse outlines savings in cost which may be expected from the use of long-span steel lines, but does not refer to the extra costs which outweigh the savings. For example, one pole for a 500-ft. span steel line would cost about $2\frac{1}{2}$ times as much as a pole for a 250-ft. span on a 0·025 sq. in. copper line, the number of stays will be doubled or trebled, steelwork and fittings are much heavier, a greater number of component parts are introduced, kicking blocks should be fitted and, finally, the introduction of an extra pole or angle position increases the cost of the line disproportionately.

The paper does not suggest that lines should be built to follow hedgerows, but it points out that the design permits this to be easily done where unavoidable.

Mr. Rowson asks for a qualification of the statement in Section (13) regarding the comparison between 7/14 S.W.G. steel and 0·025 sq. in. copper. The qualification is actually contained in the example quoted.

The bolts shown in Fig. 1 are in the correct position and provide a symmetrical arrangement of conductors. Using current regulations as a basis, the wind pressure on a 0·04 sq. in. conductor on a span of 330 ft. would be only 140 lb., and this would not in any way adversely affect the pole top.

Although the jumper lead shown in Fig. 3 appears rather flexible, it has been proved in practice to be quite sound and there is no necessity to introduce a pilot insulator as a support.

The suggestion that costs should be reduced and impulse flashover values increased by omitting the earth wire and all earthing of ironwork would contravene clause 17 of the Electricity Commissioners' Regulations E.L.C.53 (revised). The special consent of the Commissioners is necessary before any h.v. line may be operated with unearthed ironwork. This consent has been given in certain cases and experiments have been, and still are being, conducted, but are not sufficiently advanced to permit a general recommendation that unearthed ironwork principles should be adopted for h.v. lines, even after necessary reservations have been made.

Petersen coils cannot of course be used on systems employing an earthed phase, but it is not anticipated that individual combined h.v./l.v. networks will be sufficiently extensive in themselves to warrant the installation of a coil.

The possibility of a broken earth wire was foreseen and, in order to reduce the risk of an open circuit, connectors at section points are duplicated. During 4 years' operation no trouble of this sort has been experienced.

I note that Mr. Rowson does not agree that the capacity of a single-phase system is one half that of a 3-phase system. Mr. Rowson, however, uses different voltages from those given in Table 1 and also introduces 460/230-V 3-wire in his quotation. Table 1 must of course be read only in connection with the voltages given in the Table. The capacity of an 11-kV or 6·6-kV single-phase system is half that of an 11-kV or 6·6-kV 3-phase system respectively.

Difficulties arising owing to the increased cost of single-phase motors are largely a matter of economics. A decision as to whether an extension should be single-phase or 3-phase depends largely upon the type of load to be delivered. It has been found that when only a few motors are required the installation of a single-phase system does not, owing to the extra cost of single-phase motors, prevent development of power load. In many cases schemes could not have been carried out economically if 3-phase systems had been employed purely to assist a few consumers to purchase less expensive motors.

Regarding Sections 13 and 21 of the 1937 Regulations, the 6·6-kV circuit is protected by fusegear at the h.v./h.v. transformer and the l.v. circuits are each protected by

fuses on the l.v. side at the transformer pole. Each h.v./l.v. transformer can of course be readily isolated by means of the live line connectors referred to in Section 11(*c*).

When necessary, sections of the l.v. network may be interconnected by suitable fuses as explained in Section (12), but earthing must not be carried out at more than one transformer without the consent of the Electricity Commissioners as it would result in multiple earthing on the l.v. network.

I am pleased to confirm that conservator tanks are omitted on all h.v./l.v. transformers now being used on combined h.v./l.v. schemes, this step having been taken purely for reasons of economy. In the earliest combined schemes conservators were fitted, hence their appearance in the photographs.

Mr. Whysall does not anticipate many cases occurring where h.v./l.v. construction could be employed with advantage, and I can readily appreciate that this may be the case in the Belfast rural area, which represents less than 60 square miles. There is, however, no doubt as to the practical application of this system in larger areas.

Pole steps fitted 6 ft. below the highest l.v. conductor have proved quite satisfactory for all normal purposes. Heavy work cannot be carried out from this position and it is not intended that it should be, because in those cases both the h.v. and l.v. sections must be disconnected.

DISCUSSION ON "RECENT PROGRESS IN POWER RECTIFIERS AND THEIR APPLICATIONS"*

WESTERN CENTRE, AT BRISTOL, 12TH FEBRUARY, 1940

Mr. F. P. Phillips: Rectifiers of the pumpless steel-tank and glass-bulb types have the anodes mounted in extensions to the main vessel, and the arc has a long and (usually) indirect path to the cathode. In contrast, the author's slide illustrating an igniter type of rectifier showed the anode close to and immediately above the cathode. I should like to know why this simpler and apparently more efficient arrangement cannot be applied to the ordinary type of rectifier.

Mr. B. C. Robinson: While the development of rectifiers has been bound up with traction loads, there are many special conditions of supply which provide opportunities for the use of rectifiers. For instance, I had occasion recently to install a glass-bulb rectifier at a sanatorium, the conditions being that it should be suitable for operating in parallel with existing steam-driven generators. The generators are compound-wound and have a slightly drooping characteristic. The operation of this scheme both as regards change-over and also as regards working in parallel is highly satisfactory and no skilled attention is required.

I should like to ask what particular features of design are involved when a glass-bulb rectifier is to operate in parallel with steam-driven generators. Is such an arrangement fairly usual?

Mr. B. C. Lee: I should be glad if the author could give me some information about the function of the second grid, shown on one of his slides.

I understand that there are two reasons why hot-cathode rectifiers sometimes give trouble: (1) They sometimes fire sporadically, owing presumably to stray interference from other apparatus. (2) During a conducting period the arc suddenly extinguishes itself and is then re-established. Is the ignitron superior in this respect to the hot-cathode variety?

Mr. H. R. Beasant: Experience has shown the glass-bulb rectifier to be very reliable and useful, but one has to recognize the added risk of present circumstances when a bomb, without scoring a direct hit, might put an important substation out of action by causing failure of a glass bulb. The newer pumpless steel type of rectifier would therefore seem a desirable development.

The small power rectifier, making possible unattended substations of reasonable capacity, has revolutionized ideas relating to distribution for street electric traction, leading to reduction of low-voltage (d.c.) distribution to very simple terms, and in the case of electric tramways making it possible to reduce the loading on the track, used as a return circuit. By introducing a greater degree of sectionalization the maximum current in any rail and the distance that that current has to be conveyed are reduced, and the conditions necessary to minimize liability to electrolytic action are more easily attained.

With regard to the use of mercury rectifiers at lower voltages (250 volts and below), including their use in cascade on a 3-wire system, I think the author might have emphasized the lower efficiencies obtained, owing to the voltage drop being practically constant.

Can he give any information as to (1) life of anodes; (2) loss of vacuum, and possibilities as to re-evacuation, in the pumpless steel type; and (3) the optimum sizes for the various types of rectifiers dealt with?

* Paper by Dr. W. G. THOMPSON (see *Journal I.E.E.*, **83**, p. 437).

Mr. M. G. Foster: It seems to me that some of the smaller rectifier units, particularly the pumpless steel rectifiers, give a greater output per unit of floor area than some hot-cathode mercury-vapour rectifiers that I am associated with. I should be glad if the author would confirm this.

Dr. W. G. Thompson (*in reply*): With reference to Mr. Phillips's remarks, the reason why the shorter arc path associated with the ignitron cannot be used in the normal type of rectifier is, that the latter has always the cathode spot present on the mercury surface during operation and the anodes therefore require additional screening to enable them to withstand the reverse voltage with ionization present during the idle operations of the cycle. Incidentally, it has been found that for igniters working at about 500 volts or above, additional screening is also required, so that the extremely short arc path indicated in the igniter diagram in the paper is not realized under these conditions.

Mr. Robinson raised the question of the parallel operation of rectifiers with steam-driven sets. This would depend almost entirely upon the characteristics of the d.c. generators. In the case of compound-wound generators arranged so as to have a slightly drooping characteristic, this droop may be less than the shunt characteristic usually associated with rectifiers. Where the rectifier substation is sufficiently far from the site of the d.c. generators in parallel, no difficulty is experienced. Should the machines be in the same substation, then means for adjusting the rectifier voltage to enable it to take its share of the heavier loads might prove advisable. In extreme cases where level or compounded generators are used, recourse may have to be made to grid-controlled rectifiers. I cannot bring to mind a particular instance of rectifiers operating in parallel with steam-driven d.c. generators, but parallel operation with rotary or motor convertors is fairly common, and specifications are occasionally put forward calling for parallel operation with diesel-driven d.c. generators.

Mr. Lee mentions the second grid shown in one of my lantern slides. Where two grids are used in the rectifier, one is usually arranged to operate as the de-ionizing grid providing the requisite screening of the anode and de-ionizing of the arc path at the instant of commutation. The other grid is used as a control grid to which biasing potentials are supplied, either to suppress the arc or to give the usual features of grid control. With regard to the second point raised, it is difficult to say whether the ignitron is superior to the hot-cathode rectifier without reference to a particular circuit arrangement. Misfiring of ignitron rectifiers is not entirely unknown, but whether arc "snap out" is likely to take place under normal working conditions of the igniter is extremely doubtful.

I am indebted to Mr. Beasant for his remarks about the relative behaviour of the glass-bulb and steel rectifiers under air-raid conditions, and also for his views on the influence of mercury-arc rectifiers on d.c. distribution for traction purposes. Mr. Beasant mentions the operation of rectifiers on voltages below 250 volts. It is true that lower efficiencies are obtained at these voltages compared with other types of machinery on full load, but where light-load periods are common the higher efficiency of the rectifier at the lighter loads may warrant the selection of a rectifier for the given duty, despite the lower efficiency of this type of plant at full load, with voltages below 250 volts. The anodes for ordinary types of rectifiers should last indefinitely. The pumpless steel-type rectifier can be re-pumped if required. The optimum sizes of the various types of rectifier dealt with are very hard to define without reference to specific conditions. Speaking in general terms it might be said that the water-cooled rectifier begins to become economically useful for current above 1 000 amperes, but this must be qualified by the fact that several cylinders of the steel-tank air-cooled type have also been used in parallel to give outputs of at least 2 000 amperes. Below 200 amperes the power range is almost exclusively covered by rectifiers of the glass-bulb type, but their upper limit would appear to be about 500 amperes per cylinder. Thus the pumpless steel-tank rectifier can be said not only to bridge the gap between the air-cooled and water-cooled types but also to overlap the water-cooled rectifier above 1 000 amperes and the air-cooled rectifier below 500 amperes.

In reply to Mr. Foster, the mercury-arc rectifier of the pumpless steel-tank type can give greater output per unit floor area than some of the hot-cathode rectifiers, especially as the latter may have to be enclosed in a temperature-regulating chamber.

THE VERIFICATION OF SUBSCRIBERS' NUMBERS ON DEMAND WORKING: A SUPERSONIC SIGNAL METHOD*

By W. K. BRASHER, B.A., Member,† and B. F. MOSS.‡

(*Paper received* 28*th November*, 1939.)

SUMMARY

To avoid incorrect recording of callers' numbers in a trunk exchange associated with an automatic area various expedients have been adopted, extending from the reversion of a certain percentage of originating calls to the use of an audible tone. The supersonic method described in this paper was evolved for a country in which the use of a number of languages made the problem more acute. The method is applicable to exchanges already established, and the alterations and additions to equipment are not extensive.

The introduction of "demand" or "CLR" trunk working is attended by certain difficulties when the demand exchange is attached to an automatic area. The difficulties arise from incorrect recording of the calling subscriber's number, and they result eventually in loss of revenue to the telephone administration. Incorrect recording occurs owing to a caller unintentionally giving a wrong number, or to mistakes on the part of the operator's repetition, and occasionally to intentional misrepresentation by the subscriber.

It is usual to check a certain number of demand calls either by establishing a second connection to the subscriber's line independent of the first—the second connection usually being set up through a trunk offering distributor and final selector—or by reverting the call, i.e. recording the particulars of the required number and informing the caller that he will be rung. In the first method the operator, by listening or speaking over the second path, is able to ascertain whether the number she has recorded is correct. This process, however, is subject to delays involved in listening or speaking on the line to which connection is established by the second path. Similarly, the reversion method not only adds load to the operator's duties but degrades the service which could be given to the subscriber.

To avoid the incorrect recording which involves the telephone administration in loss and causes annoyance and inconvenience to subscribers, a method has been used by some administrations in which a voice frequency-tone is sent over a path similar to that described above and is heard by the operator if the correct number has been dialled. A serious objection to this method is that the check is audible to the subscriber.

Apart from considerations of secrecy, annoyance to subscribers and additional load thrown on the operators, the chief disadvantage of all the methods hitherto used is that demand trunk-calls originated at a private branch exchange (P.B.X.) or private automatic branch exchange (P.A.B.X.) cannot be checked. Unless, therefore, through trunk booking is barred to P.A.B.X. extensions and P.B.X. operators are instructed to pass trunk calls only on one junction, which will generally be the first in the group, the number must be accepted without check and the trunk operator must be instructed in the groups of P.B.X. numbers from which she may accept such calls.

In the supersonic tone method to be described, a check embracing every call without distinction whether from regular, 2/10 P.B.X., or 11/20 P.B.X. groups can be made if desired, with negligible additional load on the operator.

When the normal risks of misunderstanding the number given by the caller are complicated by the use of more than one language, the acceptance of a number without check introduces risks which any administration would be reluctant to accept. These conditions obtain in Palestine, where the following method has been evolved for use in demand exchanges which are now being installed.

The scheme depends upon the use of a supersonic signal applied temporarily by the operator to the cord circuit which is being used for the call. A circuit for the reception of this signal is then completed via the calling subscriber's line circuit and through a separate train of switches to which is connected an amplifier which accepts the signal.

GENERAL DESCRIPTION OF THE SYSTEM (FIG. 1)

Demand positions are served by a 20 kc./s. oscillator, the output of which can be connected to the operator's telephone circuit of each position. Each operator is provided with a special dialling plug and cord to which is connected the dialling circuit of the position. When the demand operator has received the particulars of the wanted and calling subscriber's numbers, she proceeds to pass the call to the distant exchange and, while doing so, inserts the dialling plug into a jack which is connected to a special distributor having access to final selectors. This train of switches is similar to the standard trunk offering train except that the final selector in a P.B.X. unit is arranged to step over all lines except the last in a group, final selectors without relays being employed. Each jack circuit is provided with an amplifying circuit tuned to 20 kc./s.

The operator sets up the number of the calling subscriber on her keysender and proceeds with her normal function of passing the call, allowing the calling sub-

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‡ General Electric Company, Ltd.

scriber to hear its progress. Meanwhile, the special train of switches has responded to the digits sent out by the keysender and has prepared a path for the reception of the supersonic signal. The output of the 20 kc./s. oscillator is connected to the operator's telephone circuit and, consequently, is applied to the calling line via the cord circuit used for answering the call. If the number set up on the special train of switches is correct, the final selector wipers will pick up the supersonic signal which will consequently be returned via the distributor to the special jack circuit and the tuned amplifier. The output of the amplifier operates a relay, whereupon a check lamp associated with the dialling plug glows steadily to indicate that the number dialled agrees with that of the subscriber's line.

If, however, the final selector wipers do not find the supersonic signal, the accepting relay will not operate and the check lamp flashes. In such a case the operator will ask the subscriber to repeat his number when she will repeat the checking process. If the second attempt produces a flashing signal, the call will be referred to a monitor.

In the case of a call from a P.B.X., it is probable that the number given by the subscriber is not that of the line actually used but that it is the number of the first line in the group. When the final selector in the P.B.X. unit reaches the line to which it has been dialled, a signal is returned to the jack circuit to indicate that the final selector has reached a P.B.X. line but not the last line in the group. If the supersonic signal is not received, the line with which the final selector has established contact is not that of the caller and a further impulse is sent to the final selector. This cycle of operations continues until the supersonic signal is received or the final selector reaches the last line in the group. In the latter event and the supersonic signal is still not received, the check lamp glows intermittently to indicate that the number dialled does not agree with any of the lines in the P.B.X. group.

APPLICATION TO BRIDGE-CONTROL EXCHANGES

The circuit arrangements covering the application of the supersonic number-checking system to bridge-control exchanges are sufficiently similar to those for sleeve-control exchanges not to warrant reproduction here in detail. Apart from the necessary difference in the circuit arrangements surrounding the sleeve conductors of the dialling circuit and jack circuit, the circuits required are virtually identical and the general description of the checking system (Fig. 1) applies equally well to both bridge- and sleeve-control exchanges.

DESCRIPTION OF OPERATION IN SLEEVE-CONTROL EXCHANGES

The circuit arrangements for the number-checking system as developed for exchanges equipped with sleeve-control type cord circuits are shown in Figs. 2, 3, 4 and 5.

Referring to Fig. 3, relay S is operated when the plug of the dialling circuit (Fig. 2) is inserted into a disengaged jack, one of a group of checking jack circuits. Relay S operates relay SS and a circuit is completed for relay A which operates if the oscillator output is satisfactory. Relay IA operates and extends flicker earth to the sleeve of the cord circuit, causing the flicker lamp to flash. If relay A does not operate owing to failure of the oscillator, relay AA operates and disconnects the circuit for relay IA.

The operator now throws the dial key and a circuit is completed for relay DCT if the keysender is available. The flicker lamp now ceases to flash and battery is connected to the tip of the plug, whereupon relay RR in the jack circuit is operated and is followed by the operation of relay DT, which prepares a loop circuit to the distributor and disconnects the flicker earth from the sleeve circuit. Relay A releases and relay AA operates, but without effect. Relay RR now releases. Immediately the keysender is taken into use, relay KR (not shown) operates and completes a circuit for relay DKT which extends a loop from the keysender to the distributor and disconnects battery from the tip of the plug.

The operator now sets up the calling subscriber's

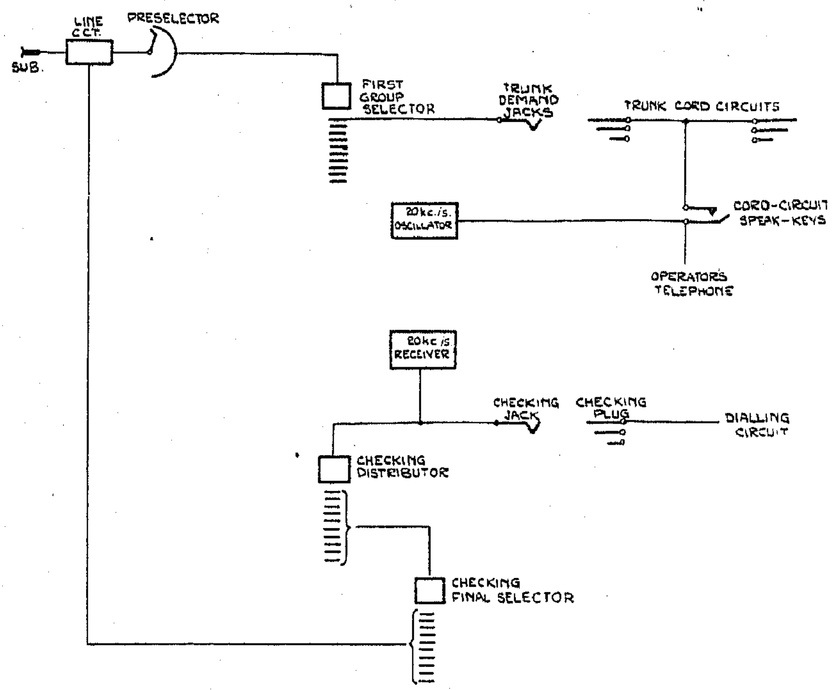

Fig. 1.—Outline of path for number-checking system.

number in the keysender, operates the start key (not shown) and restores the dial key. The keysender equipment transmits impulses to the distributor (Fig. 4) and the final selector (Fig. 5). When the keysender has transmitted the full complement of impulses, relay KR releases and opens the circuit holding relays DCT and DKT which release. Relay TCH operates during the slow-release period of relay DKT after DCT has released and operates relay CR, connects the 20 kc./s. signal to the operator's telephone and cord circuit and extends the busy lamp circuit to the sleeve of the plug, thereby operating relay LR in the jack circuit. Relay LR releases relay DT and connects a loop, consisting of the windings of relay I and the line winding of relay D, across the line wires to the distributor. Relay DT completes a circuit for relay A, which operates and releases relay AA.

The subsequent circuit operations depend upon one of the following 4 conditions:—

(1) A Successful Check on a Regular Line or on any Line in a P.B.X. Group

Relay I operates in series with the A relay in the distributor. Relay B operates and connects the super-

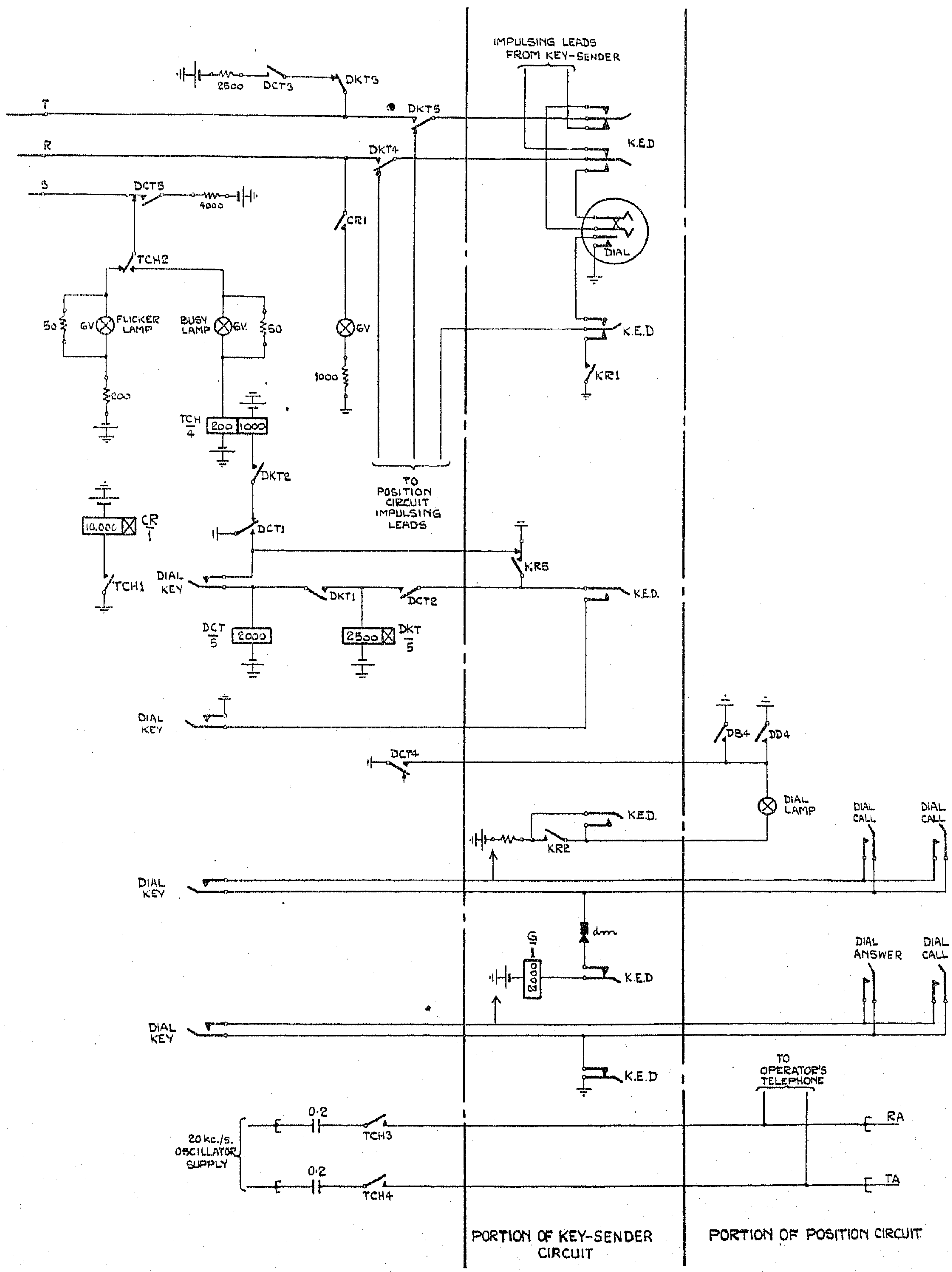

Fig. 2.—Dialling circuit.

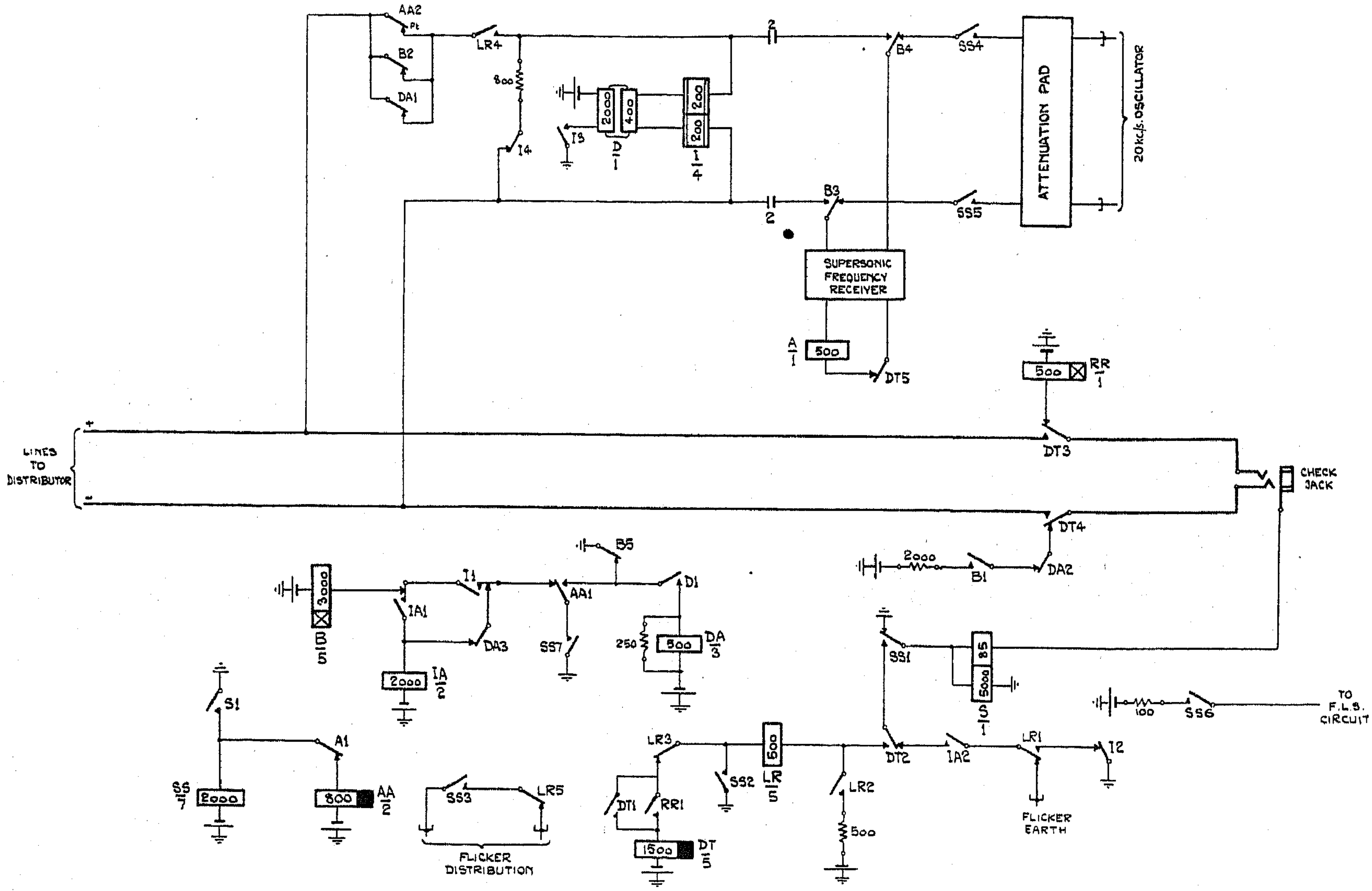

Fig. 3.—Jack circuit.

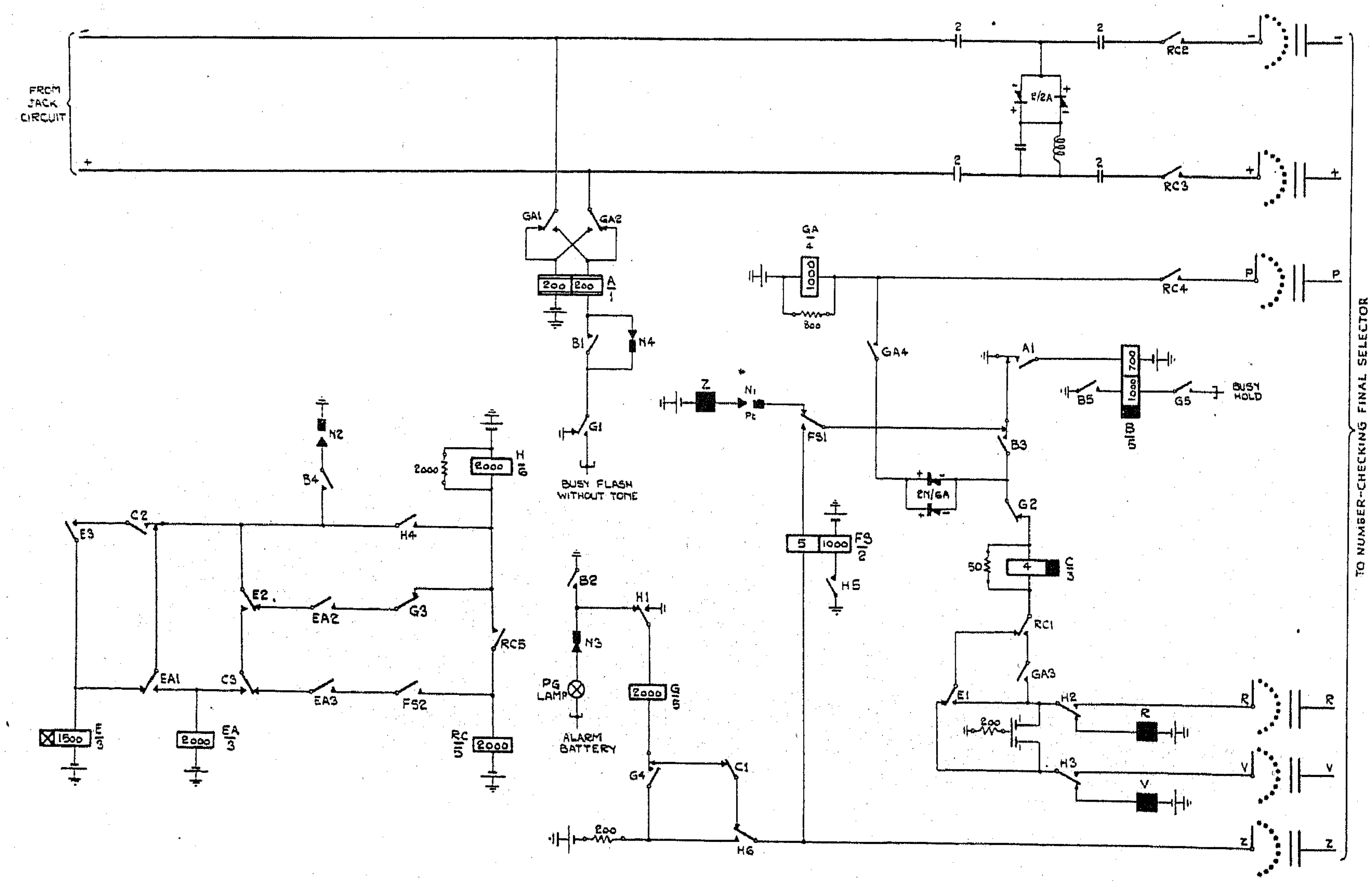

Fig. 4.—Number-checking distributor.

sonic frequency receiver to the line wires of the distributor. If the number dialled by the operator is in accordance with that of the calling subscriber's line, the output of the supersonic frequency oscillator which extends via the operator's telephone circuit to the calling line will be picked up by the final selector switch wipers and, consequently, will be received by the supersonic frequency receiver. Relay A will therefore remain operated and continue to hold open the circuit of relay AA, with the result that relay B is held and battery is applied to the ring of the check jack, causing the check lamp to glow continuously and thereby indicate a successful check of the calling line.

(2) An Unsuccessful Check on a Regular Line or on all Lines in a P.B.X. Group

If the number dialled by the operator does not correspond to that of the calling line, relay A will release when B operates, whereupon relay AA will operate and disconnect the circuit of relay B. Relay A is now connected to

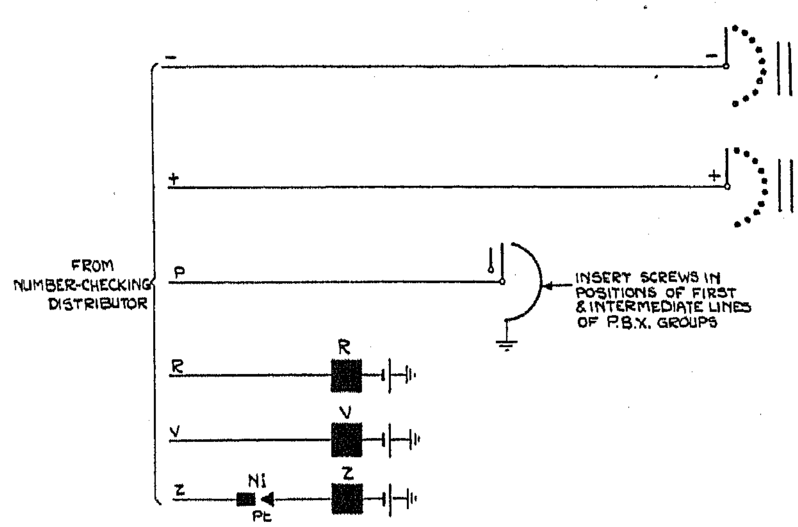

Fig. 5.—Number-checking final selector (P.B.X. 2/10).

the oscillator output and its operation causes relay AA to release, whereupon relay B re-operates and releases relay A. This sequence of operations between relays A, AA and B produces a flashing signal on the check lamp by means of the intermittent connection of battery to the ring of the jack circuit by relay B, thereby indicating that the number dialled does not correspond to the number of the calling subscriber's line.

(3) Unsuccessful Check owing to the Final Selector being engaged

In the event of the final selector being engaged, the distributor will return a busy flash signal over the line wires, whereupon relay I (Fig. 3) will release and re-operate in response to the busy flash signal. During each release period of relay I the sleeve of the jack is earthed via the low-resistance winding of relay S, with the result that the busy lamp in the plug circuit glows intermittently.

(4) Operation when a P.B.X. Group is concerned

When the first or intermediate line of a P.B.X. group is dialled, the final selector is arranged to return an earth connection to the distributor by means of an auxiliary screw arc which causes relay GA (Fig. 4) to operate and reverse the polarity of battery to the line wires. Relay D (Fig. 3) now operates and completes a circuit for relay DA.

If, however, the check indicates that the number dialled agrees with that of the calling line, relay A will remain operated as previously explained and relay AA remains released holding relay B, which opens the circuit of relay DA and connects battery to the ring of the jack to light the check lamp.

If the number dialled does not correspond to that of the subscriber's line, the operation of relay DA will introduce contacts of relays AA and B into the loop to the distributor. When relays A, AA, and B interact, the line loop is opened momentarily and one impulse is given to the distributor A relay, which repeats the impulse to the final selector rotary magnet. This sequence of operations continues until the final selector steps its wipers to a line on which the supersonic tone is picked up, or until the last line in the group is reached.

If the supersonic tone is not connected to any of the lines in the group, then when relay GA (Fig. 4) releases because the final selector wipers have reached the last line in the group, relay D releases and opens the circuit of relay DA. Relays A, AA and B continue to interact, with the result that battery is applied intermittently to the ring of the jack, causing the check lamp to glow intermittently, thereby indicating that the number dialled by the operator does not correspond to that of the calling subscriber's line.

In the event of the supersonic tone being picked up on any of the intermediate lines or the last line in the P.B.X. group, relay A remains operated by the supersonic signal received via the distributor when B is operated upon the release of relay AA. Relay B applies battery to the ring of the jack, whereupon the check lamp glows continuously.

CONCLUSION

It has been mentioned that this method provides, amongst other advantages, a means of identification of a calling line in a P.B.X. group, and it will be clear from the description that this result is obtained by the searching of the final selector for the supersonic tone. A detailed description of the application to P.B.X. 11/20 groups is unnecessary, but it should be explained that where such groups are included in an exchange it must be arranged that the checking final selector upper and lower wipers are connected together by small condensers of a capacitance suitable to pass the supersonic frequency.

In most administrations it is normal practice in demand working to allow the caller to listen to the progress of the call, in order that he may be assured that he should not leave the line. To avoid splitting the cord circuit, the operator normally uses the speaking key associated with the answering portion and, provided this is done, the receipt of the supersonic frequency by the amplifier is assured if the correct number has been set up. If, however, the normal operation procedure differs from that described, and if any appreciable use is made of the speak forward key which disconnects the caller, two small condensers must be added in each cord circuit across the speak forward key to provide a path for the supersonic frequency from the operator's circuit.

The train of switches used for checking has been described as being basically similar to the train used for trunk offering. It should be noted that the final selectors required on regular line units are the same as those used in trunk offering and testing trains; that is, they employ no relays and comprise selectors only, with the relays concentrated in the distributor circuits, of which there are a smaller proportion. In the case of final selectors in P.B.X. units these are similar to the above but are equipped with a P.B.X. arc.

It is also pointed out that while the oscillator and rectifying equipments are of necessity in the same exchange, the check selectors can be situated in a distant automatic exchange and a 2-wire circuit may be employed between the jack circuit and the check distributor circuit. The case of a central trunk switchboard controlling remote automatic exchanges is therefore covered. As, moreover, each rectifying equipment is directly associated with one trunk line, it can be adjusted, if necessary, to cover the requirements of the line to which it is connected.

The basic principle of the use of a supersonic signal in an automatic telephone exchange has been proved by test to be a practical scheme, no disturbing effect on other circuits having been noticed in a 5 000-line exchange.

In conclusion, it is emphasized that the system described forms an individual addition to the modern automatic telephone exchange, because it requires no modification to the existing circuits of exchanges already in service but merely the addition of the apparatus described above. The additional equipment on the manual switchboard is small, and the duties imposed on the operators are slight and will prove easy of fulfilment. It is claimed that the system described provides a complete number-checking arrangement, secret in operation in so far as the subscriber is concerned, free from annoyance or delay, allowing every call to be checked if desired, and essentially practicable. The annual charges on the capital cost of the apparatus will be found to be lower than the annual costs of other methods added to the value of lost calls.

AN ALTERNATIVE TREATMENT OF THE ATTENUATION OF WAVES IN A COIL-LOADED TELEPHONE LINE*

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SUMMARY

The attenuation of waves in a coil-loaded telephone line is calculated on the assumption that the line acts as a smooth equivalent and that the rising attenuation loss towards the "cut-off" is due to a multiple internal reflection effect. The reflection effect is derived analytically as a function of frequency and expressed as a "section watts reflection loss-coefficient" which gives the actual percentage power dissipated per section as a result of internal reflection. The function is evaluated for 10-lb., 120-mH, 2 000-yard cable and is shown to rise asymptotically to the known "cut-off" of the cable.

A new form of attenuation/frequency equation is then evolved from the "section watts reflection loss-coefficient" and the theoretical results are compared with very carefully controlled attenuation measurements on an actual cable. Remarkably close agreement is shown between theoretical and practical results.

The conclusion is reached that the attenuation loss in a coil-loaded line is the quantitative resultant of the smooth equivalent line loss and the loss specified by the section watts reflection loss-coefficient. The conclusion demonstrates the mechanism of transmission over coil-loaded lines.

INTRODUCTION

In his classical paper‡ on the propagation of waves in a coil-loaded line, Campbell points out that attenuation in such lines is intimately bound up with the reflection effects caused by the travelling waves impinging on the lumped inductance loads. He discusses the apparent complexity of these reflection effects which give rise to an infinite number of infinite series of waves in each loading section of the line. After suggesting that the mathematical summation of these series would probably lead to the propagation equation of the system, Campbell resorts to an alternative method of solution which avoids the necessity of summation altogether and leads direct to the propagation constant of the system. This method, used by Godfrey§ in 1898 for the analogous solution of wave propagation in a string periodically loaded with weights, involves the formulation of the two simultaneous propagation equations of a direct and a reflected wave at a loading coil. Simultaneous solution of these equations eliminates the reflection and transition coefficients of the system and leads direct to the now famous Campbell equation of the coil-loaded line, viz.

$$\text{Cosh}\, p'd = \cosh pd + Z_c/2Z_0 \, . \sinh pd$$

The purpose of the present paper is to attempt the summation of the infinite series of reflections mentioned by Campbell. The result of this summation will be found to shed further light on certain aspects of wave propagation in the coil-loaded line and may, for this reason, be of some interest to engineers.

In brief the course of the work runs as follows: By the use of suitable artifices the infinite series of power reflections are summed and the result is embodied in a function —the section watts reflection loss-coefficient—which determines the resultant percentage effective power lost per loading section by internal reflection. This coefficient is then used to develop an attenuation equation which establishes the relative functions of logarithmic decrement loss and internal reflection loss in the coil-loaded attenuation characteristic. The attenuation/frequency characteristic is shown to be due to the quantitative superposition of the resultant reflection loss on the equivalent smoothly-loaded cable. In the course of these developments the physical mechanism of the "cut-off" phenomenon is clearly demonstrated.

The theoretical results derived in Section (1) are compared in Sections (2) and (3) with carefully controlled measurements on an actual coil-loaded trunk cable circuit. Agreement between theoretical and experimental results is shown to be good in the case considered.

(1) THEORETICAL DEVELOPMENT OF THE RESULTANT INTERNAL REFLECTION LOSS AND THE ATTENUATION EQUATION

(a) Internal Reflection in the Infinite Line

Consider an infinitely long coil-loaded cable with its centre loading coil designated LPN. In the direction of propagation the coils will be numbered $LP(N+a)^{a=1, 2, 3, 4, \text{etc.}}$ and in the direction of origin $LP(N-a)^{a=1, 2, 3, 4, \text{etc.}}$ as shown in Fig. 1. The effective characteristic impedance and propagation constant within the smooth sections are Z_0 and p respectively, and the spacing of the coils is d.

A forward wave A proceeds from infinity and impinges on LPN. Part of the wave suffers reflection and part is transmitted into the succeeding section. The transmitted fraction proceeds in the direction of propagation and impinges on $LP(N+1)$, where it again divides. The reflected fraction now returns towards LPN, where it

* Extract from a research thesis carried out under the auspices of the Queen's University of Belfast.
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† Post Office Engineering Department.
‡ *Philosophical Magazine*, 1903, **5**, p. 313.
§ *Ibid.*, 1898, **45**, p. 356.

undergoes a third division, and so on. It is apparent, therefore, that an infinite series of reflections will be set up with $LP(N+1)$ as their source, and each successive reflection will add its diminishing contribution to the reflected wave B proceeding from LPN. Obviously, the same reasoning applies to all other LP's succeeding $LP(N+1)$ to infinity.

The primary reflection B will thus be the resultant of the interference on the origin side of LPN of the infinite

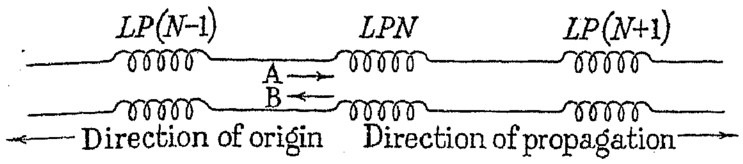

Fig. 1

number of infinite series of reflections caused by the attenuated passage of A through all the loading coils from LPN to $LP(N+\infty)$. The summation of the primary reflection thus appears to be formidable, but by the employment of a simple artifice can be completed in a single operation. This will now be considered.

Suppose the infinite line is cut on the origin side of LPN and closed through an impedance Z_0^{FC} equal to the full coil characteristic impedance of the loaded line. The direct wave A and the primary resultant reflection B will be unaffected by the change, as the reaction of the termination Z_0^{FC} on A will be the same as if the line had proceeded to infinity. The problem now reduces to the comparatively simple case of determining the power reflected from the termination of a transmission line. The new conditions are set out in Fig. 2 for analysis.

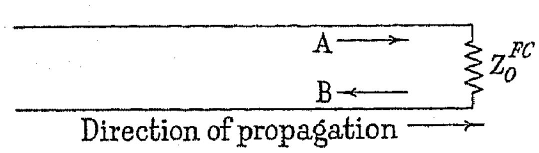

Fig. 2

Suppose as before that the effective characteristic impedance and propagation constant of the line are Z_0 and p respectively; the length of the line will be considered to be l for the present. It is required to determine the fractional effective power in watts reflected from the termination Z_0^{FC}.

Consider a wave of voltage proceeding down the length l of the line and impinging on the terminal impedance Z_0^{FC}. A potential E_r will be set up across the impedance and will differ from the potential E_d which would have appeared if the terminal impedance had been Z_0. The ratio E_r/E_d is known as the "voltage transition coefficient" K_{re}.

Since the terminal impedance Z_0^{FC} differs from the characteristic impedance Z_0 of the line, reflection will occur. If the magnitude of the reflected voltage is E_ρ then the ratio E_ρ/E_d is termed the "voltage reflection coefficient" $K_{\rho e}$.

Then from the tenets of classical theory

$$K_{re} = E_r/E_d = \frac{2Z_0^{FC}}{Z_0^{FC}(1+e^{-2pl}) + Z_0(1-e^{-2pl})} \quad . \quad (1)$$

and

$$K_{\rho e} = E_\rho/E_d = \frac{Z_0^{FC}(1-e^{-2pl}) - Z_0(1-e^{-2pl})}{Z_0^{FC}(1+e^{-2pl}) + Z_0(1-e^{-2pl})} \quad . \quad (2)$$

whence

$$K_{re} - 1 = K_{\rho e} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Similarly the transition and reflection coefficients for a current wave can be written thus:

$$K_{.i} = \frac{2Z_0}{Z_0^{FC}(1+e^{-2pl}) + Z_0(1-e^{-2pl})} \quad . \quad (4)$$

and

$$K_{\rho i} = \frac{Z_0(1+e^{-2pl}) - Z_0^{FC}(1+e^{-2pl})}{Z_0^{FC}(1+e^{-2pl}) + Z_0(1-e^{-2pl})} \quad . \quad (5)$$

whence

$$K_{ri} - 1 = K_{\rho i} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

If the voltamperes in the receiving impedance are represented by $(VA)_r$ it follows from (1) and (4) that

$$\begin{aligned}(VA)_r &= E_r I_r \\ &= K_{re} \,.\, K_{ri} \,.\, E_d I_d \\ &= K_{rei} \,.\, E_d I_d \quad . \quad . \quad . \quad . \quad . \quad (7)\end{aligned}$$

where $K_{rei} = K_{re}K_{ri}$,

$$\begin{aligned}&= \frac{4Z_0 Z_0^{FC}}{[Z_0^{FC}(1+e^{-2pl}) + Z_0(1-e^{-2pl})]^2} \\ &= 1 - K_{\rho ei} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)\end{aligned}$$

in which $K_{\rho ei}$ is the volt-amperes reflection coefficient.

If the full coil characteristic argument is θ^{FC} it follows that the effective power P_r delivered to the terminal impedance $Z_0^{FC}\underline{|\theta^{FC}}$ is given by

$$P_r = (VA)_r \cos\theta^{FC}$$

From equation (7)

$$(VA)_r = K_{rei} \,.\, E_d I_d$$

whence

$$\begin{aligned}P_r &= K_{rei} \,.\, E_d I_d \,.\, \cos\theta^{FC} \\ &= \frac{K_{rei} \,.\, E_d^2 \,.\, \cos\theta^{FC}}{Z_0} \quad . \quad . \quad . \quad . \quad (9)\end{aligned}$$

Suppose now that the potential E_d is applied to a resistance R_0 equal to the dissipative component of the line characteristic impedance $Z_0\underline{|\alpha}$.

The current in R_0 is given by

$$I = \frac{E_d}{Z_0 \cos\alpha}$$

from which it follows that the maximum effective power P_{rm} receivable in the termination if it had been equal to Z_0 is given by

$$P_{rm} = \frac{E_d^2}{Z_0 \cos\alpha} \quad . \quad . \quad . \quad . \quad (10)$$

From (9) and (10)

$$\begin{aligned}\frac{P_r}{P_{rm}} &= K_{rei} \,.\, \cos\theta^{FC} \,.\, \cos\alpha \\ &= K_{rw} \\ &= 1 - K_{\rho w} \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)\end{aligned}$$

where K_{rw} is the watts transition coefficient and $K_{\rho w}$ is the watts reflection loss-coefficient.

From equation (8) it follows that

$$K_{\rho w} = 1 - \frac{4Z_0Z_0^{FC}\cos\theta^{FC}\cos\alpha}{[Z_0^{FC}(1+e^{-2pl}) + Z_0(1-e^{-2pl})]^2} \quad (12)$$

At this point it will be convenient to simplify equation (12) somewhat. The term l refers to the distance that the current and voltage waves have travelled with propagation constant p before striking the terminal impedance. In the present analysis it has been so arranged that the waves proceed from infinity. It follows, therefore, that

$$(1 \pm e^{-2pl}) = 1$$

whence

$$K_{\rho w} = 1 - \frac{4Z_0Z_0^{FC}\cos\theta^{FC}\cos\alpha}{(Z_0^{FC} + Z_0)^2} \quad . \quad . \quad (13)$$

Referring now to Fig. 2 it follows from (13) that

$$B = A \,.\, K_{\rho w} \quad . \quad . \quad . \quad . \quad . \quad (14)$$

(b) Summation of the Infinite Series of Section Reflections and Development of the Section Watts Reflection Loss-Coefficient

Referring again to Figs. 1 and 2, it is apparent that if the direct power wave A is unity, then the primary resultant reflected wave B will be $K_{\rho w}$ watts, and K_{rw} watts will be absorbed by the load as a result of this first division. It is now necessary to consider the be-

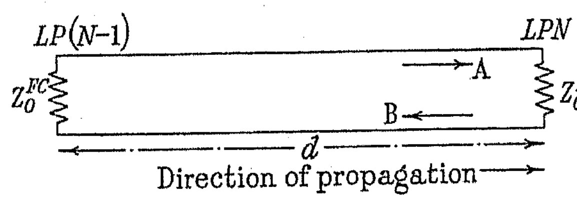

Fig. 3

haviour of the reflected wave B as it proceeds in the direction of origin. As the wave approaches loading coil $LP(N-1)$ it meets with the same conditions as confronted the direct wave A when it impinged on LPN. The reflected wave B will therefore set up an infinite number of infinite series of sub-reflections as it proceeds to infinity in the direction of origin. To sum these reflections automatically the line must be considered to be cut at $LP(N-1)$ and closed through the full-coil characteristic impedance Z_0^{FC}. The analytical circuit conditions are now set out in Fig. 3. The primary resultant reflection B will arrive at $LP(N-1)$ with magnitude $(K_{\rho w} \,.\, e^{-2pd})$ and after division will be reflected back in the direction of propagation arriving at LPN with magnitude $(K_{\rho w} \,.\, e^{-2pd})^2$. This sequence of sectional reflections will be continued an infinite number of times, and on each arrival of the reflected wave at LPN its magnitude will be $(K_{\rho w} \,.\, e^{-2pd})^{2n}$, where n is the number of times the wave has passed up and down the section length.

Each time the reflected wave arrives at LPN a fraction of the power will be absorbed by the local impedance and will augment the power transmitted in the direction of propagation.

Suppose k_{rw} = resultant at LPN of the primary transmission and the infinite series of secondary transmissions having their origin in reflection from LPN.

Then

$$\begin{aligned} k_{rw} &= K_{rw} + (K_{\rho w} \,.\, e^{-2pd})^2 \,.\, K_{rw} \\ &\qquad + (K_{\rho w} \,.\, e^{-2pd})^4 \,.\, K_{rw} + \ldots \\ &= K_{rw}(q^0 + q^2 + q^4 + \ldots + q^\infty) \quad . \quad . \quad . \quad (15) \end{aligned}$$

where $q = K_{\rho w} \,.\, e^{-2pd}$

Summing (15) to infinity,

$$k_{rw} = \frac{K_{rw}}{1 - q^2} \quad . \quad . \quad . \quad . \quad . \quad (16)$$

since $q < 1$

Equation (16) gives the resultant watts transition coefficient k_{rw}. If the resultant power reflection loss is denoted by $k_{\rho w}$, then

$$k_{\rho w} = \left[1 - \frac{K_{rw}}{1 - q^2}\right]$$

The function k_{rw} is the ratio of the power absorbed into the infinite coil-loaded line to the power which would have been absorbed if the infinite line had been smooth. Function $k_{\rho w}$ is analogously defined. It follows, therefore, that the power lost by reflection per section length d of the coil-loaded case in terms of the power absorbed by the same length of the smooth equivalent line is given by $k'_{\rho w}$,

where

$$k'_{\rho w} = (1 - e^{-2pd})k_{\rho w} \text{ watts per watt} \quad . \quad (17)$$

in which p is the propagation constant of the smooth equivalent.

Function $k'_{\rho w}$ is termed the "section watts reflection loss-coefficient" and, if multiplied by 100, gives the percentage power in watts lost in each loading section of the line as a result of internal reflection. It is derived experimentally in Section (2), where it is shown to rise asymptotically to the cut-off frequency ordinate in a manner closely analogous to the attenuation characteristic.

(c) Development of an Attenuation Equation for the Coil-loaded Line in terms of the Section Watts Reflection Loss-Coefficient $k'_{\rho w}$

For the purpose of developing an attenuation equation for the coil-loaded line in terms of $k'_{\rho w}$ it will be assumed that, basically, the coil-loaded line acts for propagation purposes as a smooth line with an equivalent weight of continuously distributed loading. The difference between the attenuation coefficients of the coil-loaded and the continuously equivalent loaded line will be considered to be due entirely to the power reflection effects analysed in the previous sub-sections. The validity of this assumption will be tested in Section (3).

For purposes of brevity in what follows, the hypothetical line with smooth or continuous equivalent loading will be described as the C.E.L. line. Its weight of loading per mile will be $(L_c/d + L)$, where L_c is the loading-coil inductance and L is the natural inductance per mile of the unloaded conductor used in the coil-loaded line.

Consider two cables, one with C.E.L. and the other with coil-loading stretching to infinity in either direction. At the centre of each cable consider a length d and let:—

p = propagation constant of C.E.L. line,
$= \beta + j\alpha$
p' = propagation constant of coil-loaded line,
$= \beta' + j\alpha'$
d = coil spacing,
= length of unit analytic sections considered at the centre of both lines,
P_S = power entering unit section of C.E.L. line,
P_R = power leaving unit section of C.E.L. line,
$P = P_S - P_R$
= power absorbed by unit section of C.E.L. line,
P'_S = power entering unit section of coil-loaded line,
P'_R = power leaving unit section of coil-loaded line,
$P' = P'_S - P'_R$
= power absorbed by unit section of coil-loaded line,
k'_{pw} = section watts reflection loss-coefficient.

In the case of the C.E.L. line, the attenuation propagation over the unit section is described by

$$P_S/P_R = e^{2\beta d}$$

and, if the input power is unity,

$$P_R = e^{-2\beta d}$$

whence

$$P = (1 - e^{-2\beta d})$$

It follows from equations (11) and (17) that the power absorbed by the unit section of coil-loaded line is given by

$$P' = (1 - e^{-2\beta d}) + k'_{pw}$$
$$= 1 - P_R$$

Since P_S is made equal to unity for equivalence of the two cases,

$$e^{-2\beta' d} = e^{-2\beta d} - k'_{pw} \quad . \quad . \quad . \quad . \quad (18)$$

which specifies the attenuation coefficient of the coil-loaded cable in terms of the logarithmic decrement loss of its smooth equivalent and the power reflection loss-coefficient k'_{pw}.

(2) EXPERIMENTAL APPLICATION

(a) Introduction

Verification of the results derived in Section (1) depend largely on the accurate measurement of the attenuation characteristic of the coil-loaded line. The characteristic has been measured by three different methods for a 10-lb., 120-mH, 2 000-yard cable, and brief notes on the precautions taken to ensure accuracy are given in sub-section (*b*). The section watts reflection loss-coefficient and the derived attenuation equation are evaluated for the 10-lb., 120-mH, 2 000-yard cable in sub-section (*c*).

(b) Measurement of the Attenuation Characteristic

The attenuation of the line is defined by the expression

$$\beta' = \frac{20}{l} \log_{10} \frac{V_S}{V_R} \text{ decibels}$$

where l = length of line terminated by Z_0,
V_S, V_R = sent and received voltages, respectively.

The three methods used for the measurement were:—

(i) Meyer's method (open termination).
(ii) Meyer's method (Z_0 termination).
(iii) Direct valve-voltmeter measurement of sent and received voltages.

Meyer's method is too well known to require description here, but a note on the make-up of the Z_0 termination for method (ii) may not be out of place. For precision work the termination must be a perfect characteristic impedance and is best built up of a long length of the same type of line as that used for the actual test length. In practice a 150-mile length of 10-lb., 120-mH, 2 000-yard line closed at its far end by $\sqrt{(L/C)}$ ohms proved to be a perfect termination entirely unaffected by far-end reflection.

The two variations of Meyer's method gave very consistent results, varying from each other over most of the frequency range by less than 2 %. The two sets of results are plotted in Fig. 4, and a single curve is drawn through the individual measurements.

One of the chief disadvantages of Meyer's method is its progressive insensitivity in the higher frequency range. The limit of its application is about $0 \cdot 9 f_c$, and it is useless for an accurate estimate of the cut-off frequency. To get over this difficulty a direct valve-voltmeter method has been evolved and has proved to be successful.

The valve-voltmeter method is briefly as follows: A test length of approximately 30 miles of 10-lb., 120-mH, 2 000-yard cable is arranged with its sending and receiving ends available at a common test point. Power is fed from a high-grade variable oscillator to the input of the line, which is closed at its far end by the perfect Z_0 used in method (ii). A high-impedance valve-voltmeter is so arranged that it can be switched at will across the input or the output of the line. To carry out a measurement, the oscillator is set to a predetermined frequency and the power input adjusted to some suitable constant value. Valve-voltmeter readings are then taken at both sending and receiving ends of the line. The voltmeter is then switched across the variable arm of a non-reactive potentiometer fed with power from the oscillator, and the slider adjusted to give the same readings on the voltmeter as were recorded at the sending and receiving ends of the line. Since the potentiometer is non-reactive, the ratio of the potentiometer resistance readings is equal to the ratio of "sent" and "received" voltages. If R_S and R_R are the potentiometer resistances corresponding to the voltmeter readings for sending-end and receiving-end voltages respectively, then

$$\beta' l = 20 \log_{10} R_S/R_R$$

By suitable design of the valve-voltmeter system and use of a Sullivan 1 000-ohm slide-wire as a potentiometer, the method can be used with a high degree of accuracy for attenuations ranging up to 30 db.

Experimental results by the direct method are also shown in Fig. 4, which indicates that the cut-off frequency is slightly in excess of 3 200 c./s. for 10-lb., 120 mH, 2 000-yard cable.

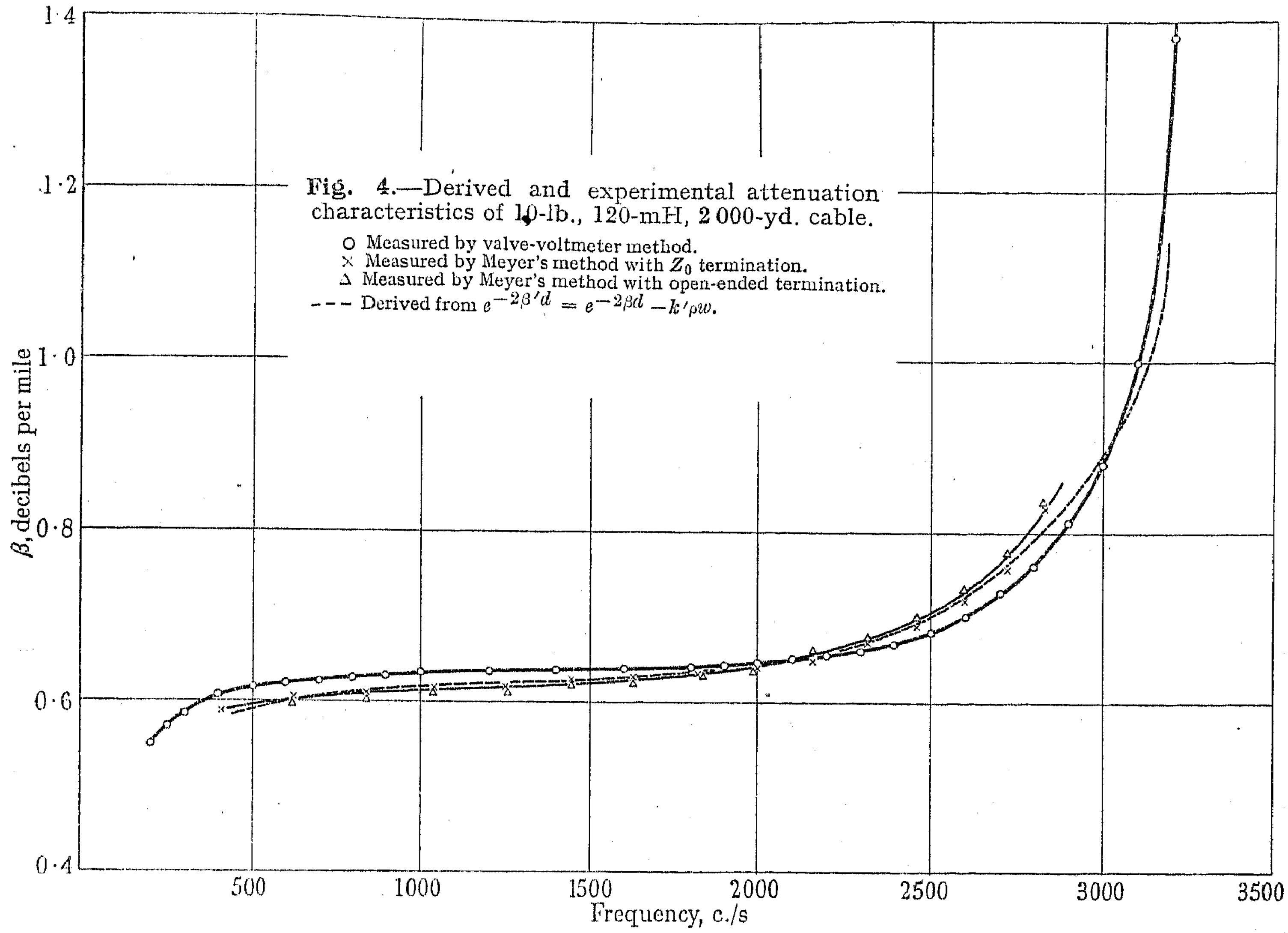

Fig. 4.—Derived and experimental attenuation characteristics of 10-lb., 120-mH, 2 000-yd. cable.

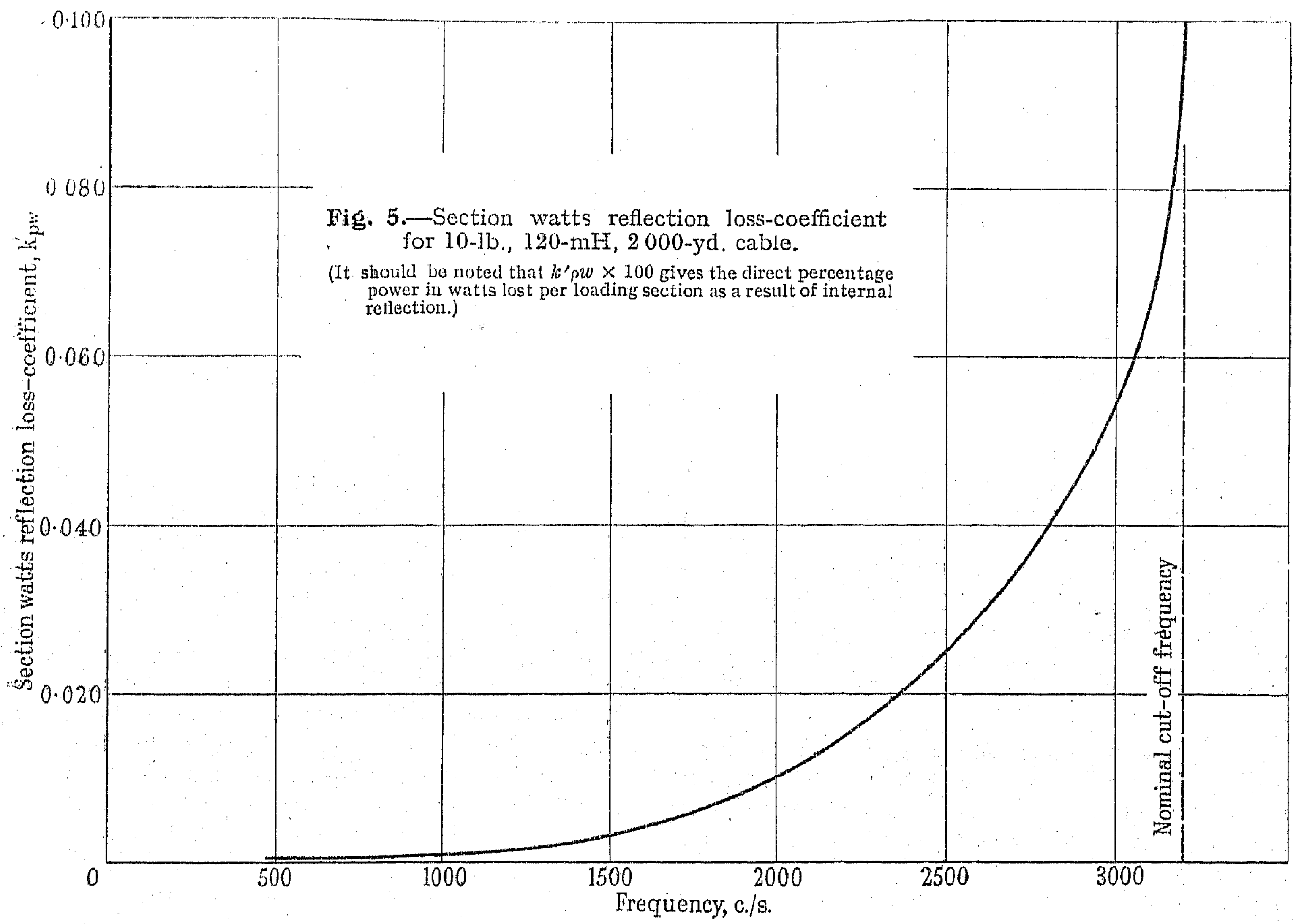

Fig. 5.—Section watts reflection loss-coefficient for 10-lb., 120-mH, 2 000-yd. cable.

(It should be noted that $k'_{pw} \times 100$ gives the direct percentage power in watts lost per loading section as a result of internal reflection.)

(c) Evaluation of the Section Watts Reflection Loss-Coefficient $k'_{\rho w}$ and the derived Attenuation Equation

In order to evaluate the section watts reflection loss-coefficient as defined by equations (13) and (17), it is necessary to determine the quantities $Z_0|\underline{\alpha}$ and $Z_0^{FC}|\underline{\theta^{FC}}$ over the required frequency range. The first term must be interpreted as the characteristic impedance of the continuously equivalent loaded (C.E.L.) line and is calculated from the usual classical formula

$$Z_0|\underline{\alpha} = \sqrt{\frac{R + j\omega L'}{G + j\omega C}}$$

where $L' = (L_c/d + L)$

equation (18) leads directly to the derived attenuation equation. This has been calculated up to the cut-off frequency, and the characteristic is included in Fig. 4 with experimental characteristics. Agreement between derived and experimental results is seen to be reasonably good.

(3) CONCLUSIONS

(a) Power lost in the Coil-loaded Line by Internal Reflection

As stated in the Introduction, it was the primary object of this work to determine the power lost per loading section by multiple internal reflection. The infinite number of infinite series of power waves traversing a loading section has been summed and used in conjunction

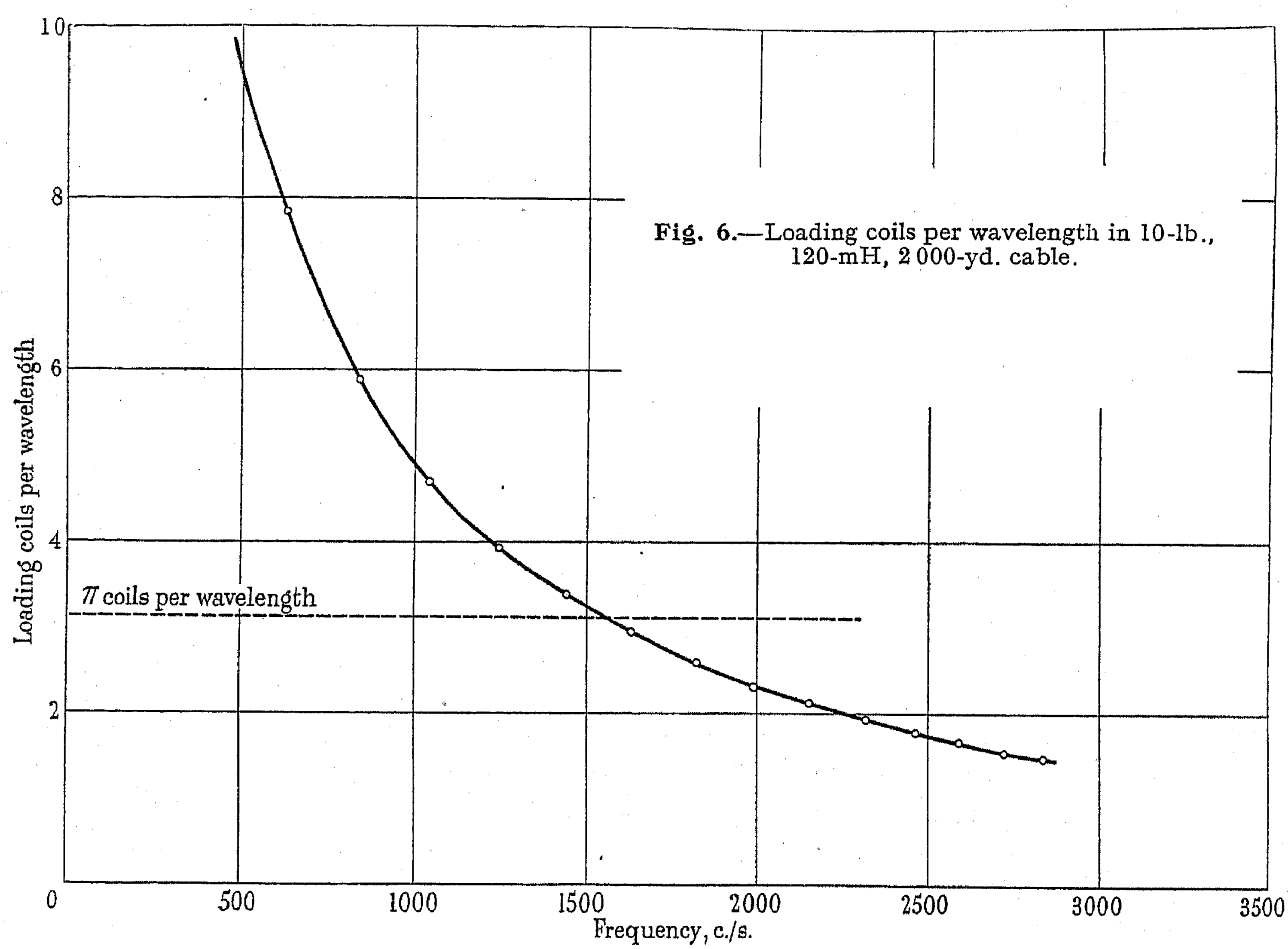

Fig. 6.—Loading coils per wavelength in 10-lb., 120-mH, 2 000-yd. cable.

Determination of the full-coil characteristic impedance presents more difficulty and is, perhaps, most easily achieved by practical measurement. In the present instance a 150-mile length of 10-lb., 120-mH, 2 000-yard cable was terminated with $\sqrt{(L'/C)}$ ohms, and impedance measurements were made at the full-coil position at the sending end. The bridge used was a standard resistance-capacitance set with certain modifications to extend its range.

Substitution of the calculated and measured characteristic impedances in equations (13) and (17) gives the frequency characteristic of the section watts reflection loss-coefficient $k'_{\rho w}$. The characteristic is set out in Fig. 5 and is discussed in the next Section.

Application of the reflection loss function $k'_{\rho w}$ to

with the reflection and transition coefficients of the coil-loaded line to derive a new expression—the section watts reflection loss-coefficient. This coefficient can be determined from impedance measurements on the line and gives the direct percentage loss of effective power per section due to internal reflection.

The coefficient $k'_{\rho w}$ has been derived from impedance measurements on a 10-lb., 120-mH, 2 000-yard cable and has been shown to be closely analogous to the attenuation characteristic. Thus, below 1 500 c./s. the effective power loss (see Fig. 5) is seen to be less than 0·3 % per section; above 1 500 c./s., however, the loss increases rapidly and progressively to a value approaching 10 % at the cut-off frequency.

It may be concluded, therefore, on the evidence offered

by the characteristic of the section watts reflection loss-coefficient, that the cut-off phenomenon is largely, if not wholly, due to multiple internal reflection loss.

(b) The Reflection-Attenuation Equation

Assuming that the coil-loaded line acts, at all frequencies up to the cut-off, as if the loading were uniformly distributed and that the rising attenuation characteristic is due solely to the superposition of the section watts reflection loss-coefficient k'_{pw}, it has been found possible to derive a new attenuation equation. This takes the form

$$e^{-2\beta' d} = e^{-2\beta d} - k'_{pw}$$

Using the measured characteristic (Fig. 5) for the coefficient, the attenuation characteristic of the coil-loaded line has been calculated from the above equation and compared with results obtained experimentally under carefully controlled conditions.

The attenuation characteristic derived from the reflection-attenuation equation gives results in close accord with the direct experimental results. The maximum variations between the derived characteristic and the experimental characteristics at any part of the frequency range are as follows:—

Characteristics	Maximum variation
(1) Derived and Meyer's method ..	2·0 %
(2) Derived and valve-voltmeter method	3·7 %

These variations are considered to be sufficiently small to justify the assumptions made in the development of the reflection-attenuation equation.

It may be concluded, therefore, that the attenuation characteristic of the coil-loaded line is the quantitative resultant of the smooth equivalent line loss together with the loss specified by the section watts reflection loss-coefficient k'_{pw}.

It follows that the cut-off phenomenon is due wholly to the section watts reflection loss-coefficient.

(c) Test of Conclusions by Application of the π Criterion

A well-known criterion, directly derivable from Campbell's equation, states that there must be at least π loading coils per wavelength for efficient transmission. In other words, if there are less than π coils per wavelength the attenuation will tend to become excessive. It will be a test to see whether the conclusions arrived at in the previous sub-section harmonize with this criterion.

The phase or wavelength coefficient α' was measured by the Meyer method on the same 10-lb., 120-mH, 2 000-yard cable as was used for the attenuation measurements. From the coefficient α' the number of coils per wavelength has been derived, the results being set out in Fig. 6. Inspection of the characteristic shows that at all frequencies above 1 550 c./s. there will be less than π coils per wavelength—it may be expected, therefore, that transmission above this frequency will become increasingly impaired. If cross reference is now made to the section watts reflection loss-coefficient k'_{pw} in Fig. 5, it will be apparent that 1 550 c./s. is the point at which the power reflection loss begins to rise appreciably in its asymptotic approach to the cut-off.

It is apparent, therefore, that the conclusions arrived at in the previous sub-section are in harmony with the criterion of π coils per wavelength.

WIRE BROADCASTING INVESTIGATIONS AT AUDIO AND CARRIER FREQUENCIES

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SUMMARY

The general principles underlying the design of wire broadcasting systems for the distribution of programmes at audio and carrier frequencies are considered. In Part 1, relating to audio frequency, questions concerning the remote control of receiving and amplifying stations are discussed. Details of tests on distribution cables are given, and it is shown that, with any particular load, attenuation can be rendered reasonably constant over the audio-frequency band.

In Part 2 brief consideration is given to the utilization of electricity supply networks for the distribution of programmes at carrier frequencies. The theoretical and practical aspect of the utilization of telephone lines for the same purpose is treated in greater detail.

LIST OF SYMBOLS

α = attenuation.
β = phase constant.
γ = propagation constant.
ϵ = base of napierian logarithms.
η = efficiency.
f = frequency.
l = spacing of line amplifiers or a length of line.
r = radial distance of any subscribers from central point of supply.
R, R_a = radii of areas around central point of supply of carrier.
m = modulation factor.
n = density of subscribers or a whole number.
N = total number of subscribers.
P = total low-frequency input power to amplifiers.
p_i = input carrier power to one amplifier.
p_o = output carrier power from one amplifier.
q = number of carrier channels.
V, V_r, V_s = voltages as in text.
Z_0 = line characteristic impedance.
Z_r: Z_s = line terminating and sending-end impedance, respectively.

INTRODUCTION

The idea of conveying music and speech over a wire network is by no means new. In England as early as 1895, the Electrophone Company, using the National Telephone Company's lines, provided service to subscribers from theatres, music halls, and churches. About 12 years earlier, music had been transmitted from a theatre to listeners in an hotel. Until a few years ago, however, no development took place. The indifferent quality of the service, the absence of suitable loudspeakers and amplifying equipments, the high cost involved, and the lack of public demand, were the root causes of this stagnation. Later the introduction of radio broadcasting, which by its novelty made a great public appeal and by its diffusibility enabled all homes within wide areas to receive the radiated programmes without undue delay and expense in the provision of a service, seemed to seal the doom of wire broadcasting. However, the very success of radio broadcasting, coupled with its limitations, has caused the rebirth of wire broadcasting.

The universality of radio broadcasting has resulted in a state of interference and a restriction in audio bandwidth from which wire broadcasting systems have comparative freedom. So far, in Great Britain little headway has been made with wire distribution since only about 3 % of the total number of listeners receive their programmes by wire. In Holland, however, over 50 % of the listeners use the wire network; in Switzerland the percentage is about 16, whilst in Germany it is stated that, chiefly for political reasons, plans have been made to provide 10 million listeners[1] by means of carrier currents over the telephone network. In Great Britain there is reason to expect a considerable extension of wire broadcasting reception when conditions become more favourable.

Reliability of Radio and Wire Broadcasting

Although it is true that a suitable wire broadcast system is freer than a radio broadcast system from interference of various types—atmospheric, industrial plant, radio stations—and is not subjected to the limitation of band width suffered by radio emissions in a frequency-congested medium, it must be admitted that the fault liability of a system of distribution utilizing a wire network is potentially greater than that of a radio system. The failure of one cable might render inoperative thousands of sets. Against this disadvantage is the fact that modern cables are remarkably free from faults. Moreover, as far as the home service is concerned, since the programmes can be transmitted over lines direct from the broadcasting studios a wire broadcast system would not be affected by failure of the radio transmitting plant and aerials.

Comparative Costs of Radio and Wire Broadcasting Reception

With regard to comparative costs, the general assumption is that any wired broadcasting system must necessarily be dearer than direct radio reception owing to the high cost of the wire network. Such an assumption might be misleading and, without an examination of all the factors, is not justified. Assuming it were possible to start afresh, a true comparison of a radio system against a wired audio system would take account of the radio transmitting plant and listeners' receiving sets in the one

* Wire Broadcasting Branch, General Post Office.

case, and the amplifying plant, the wire networks and listeners' loud-speakers in the other case. The criterion would be the comparative cost of reproducing, at the listener's home, programmes of substantially the same quality by the two systems. Such a comparison is beyond the scope of this paper. It is, however, of interest to view the matter of cost from the listener's viewpoint. The average listener would not concern himself with refinement of accountancy, so that if he bought a receiving set for, say, £10 and expected it to last, say, 6 years, he would regard this as costing him £1 13s. 4d. per year. If he used his set for 5 hours per day—the average peace-time figure arrived at by the author as the result of extensive inquiries—his valve and other component replacements would cost him about 15s. per year, making a total of £2 8s. 4d. per year, exclusive of licence, electricity or battery supplies, servicing and incidentals. If he had a mains electricity supply and adopted the "all in" system of payment, cost of electricity would be negligible. On the other hand a large proportion of the listeners would not adopt the "all in" system and many would have slot meters, paying about 4d. per unit for electricity, making a weekly cost of 8d. for current. The total cost to the listener would therefore be of the order of 1s. 7d. per week, exclusive of licence fee, servicing and incidentals. If he lived in the country, where electricity charges are higher, or if he had a battery set, the cost to him would be appreciably greater than the figures quoted. Failure of the receiver and the consequent cost of replacements and servicing would increase the cost appreciably.

In Great Britain the average charge for a two-programme service made by wire broadcasting relay companies is a little less than 1s. 6d. per week, to which must be added the charges for a loud-speaker. Thus, under the conditions assumed, the cost to the listener under the two systems is approximately the same. The inveterate listener, satisfied with two programmes, would find an audio wire broadcasting system cheaper than a radio system, whilst the occasional listener would be better suited from the cost aspect by a radio service.

SYSTEMS OF WIRE BROADCASTING

The various systems of distribution by wire can be grouped under two main classes, (1) audio frequency, and (2) carrier frequency.

PART 1. WIRE BROADCASTING AT AUDIO FREQUENCIES

The audio system of distribution can make use of existing telephone pairs and by means of a suitable selecting device can enable listeners to choose one of several programmes available at the exchange. In general, however, electrical energy cannot be sent over the lines at sufficient volume to work loud-speakers direct without causing considerable interference with telephone circuits in the same cable. Thus an amplifier is needed at each listener's premises, which increases the cost considerably. Obviously a telephone conversation and a broadcasting programme cannot be received simultaneously on the same pair of wires. The system has been in operation in Switzerland for a few years. It is significant, therefore, that in an article on high-frequency telephone broadcasting in Switzerland Dr. Keller[2] appears to be turning from this system to a carrier system as a means of providing a more satisfactory service.

A more suitable audio system is one in which a separate wire network is used to distribute programmes at loud-speaker strength from a central amplifying station. Two variants are possible; the first provides for several pairs, one for each programme, direct from the distribution station to the selector switch in the listener's premises; the second provides for pairs to suitable points at which electrically operated switches are fixed to enable the listener to send switching currents along the single pair extending from his house to the switching position, and so select one of several programmes. Which of the two variants is employed depends upon local circumstances. In sparsely populated districts, for example, the cost of providing several pairs over the whole distance between the amplifying station and listeners' premises might be greater than the cost of providing several pairs part of the way to a switching position, installing switching equipment, and running a single pair from this position to the listener's premises. In general, however, the capital and maintenance costs of the switching equipments are greater than the saving in wire connections.

Remote Selection of Programmes

On the technical side the remote switching system has many interesting features, and a considerable amount of ingenuity has been displayed in devising systems and equipment that combine low capital and maintenance costs with freedom from undesirable disturbances to other circuits during switching operations.

One system utilizes two relays for each listener's circuit to enable one of four programmes to be selected. With a single pair leading from the listener's premises to the distribution position, four switching combinations are possible—the A or the B line can be separately earthed, the two lines can be earthed simultaneously, or they can be rendered unearthed simultaneously. Thus the choice of four programmes can be provided by this means. The obvious technical disadvantage of this system is the unbalancing of the lines with the consequent disturbance to circuits of other listeners, particularly those connected to the same distribution position. The effects can be mitigated to a considerable extent by suppression devices, but it is an unsound engineering principle to use appliances that have inherent defects and mitigate their disadvantages by the aid of palliatives. A diagram of this system is shown at (*a*) in Fig. 1. A second system, shown diagrammatically in (*b*) and (*c*) of Fig. 1, employs pulses to actuate a uniselector or a stepping relay at the distribution position, a simple push-button type of switch being all that is needed at the listener's premises. This system, being balanced, is free from the disturbance effects of the first.

A photograph of a stepping relay made by a well-known British firm is given in Fig. 2.

Layout of Audio System

An ideal layout of a wire broadcasting system intended to supply a large town with several programmes, both

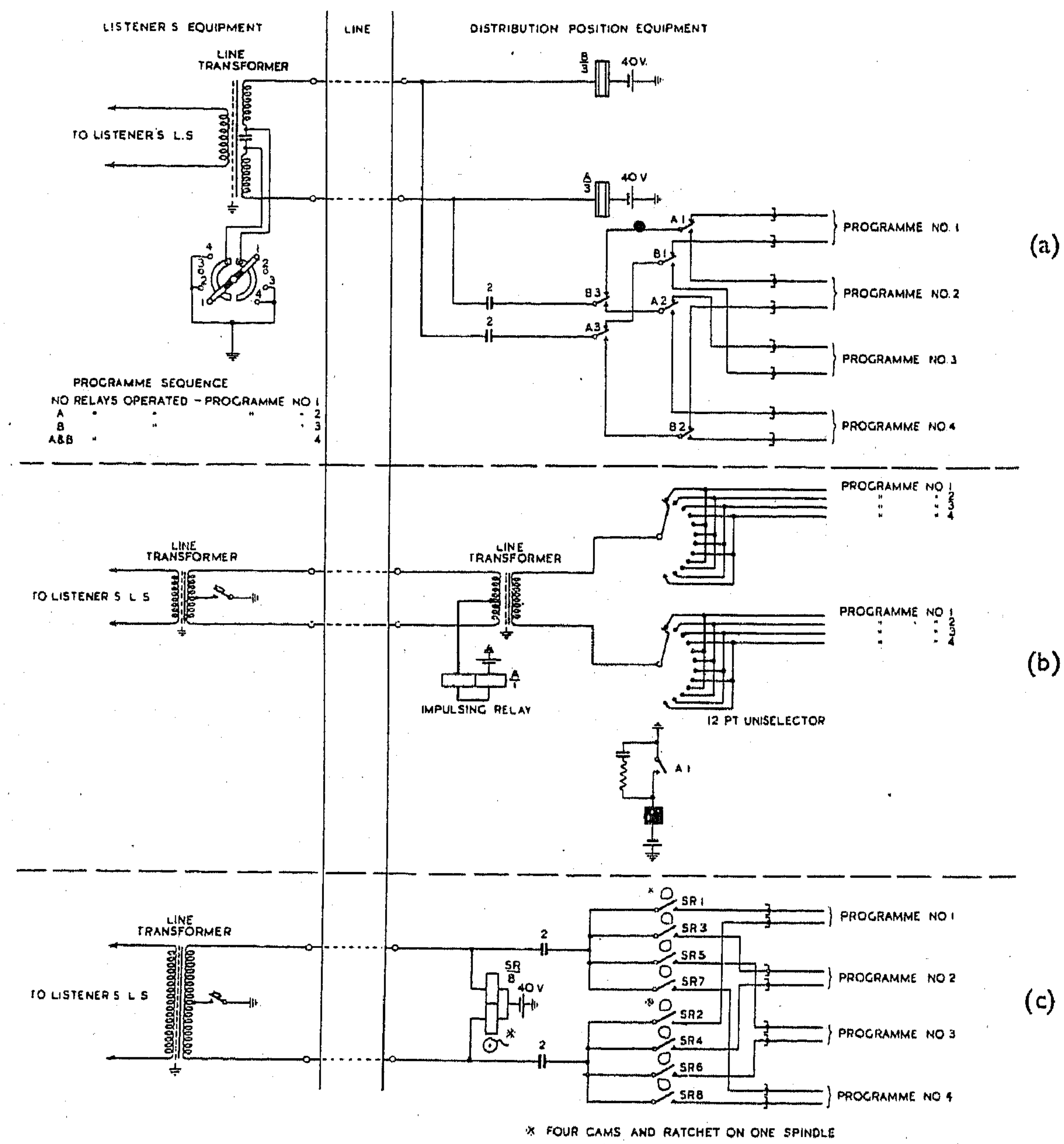

Fig. 1.—Remote selection of programmes.

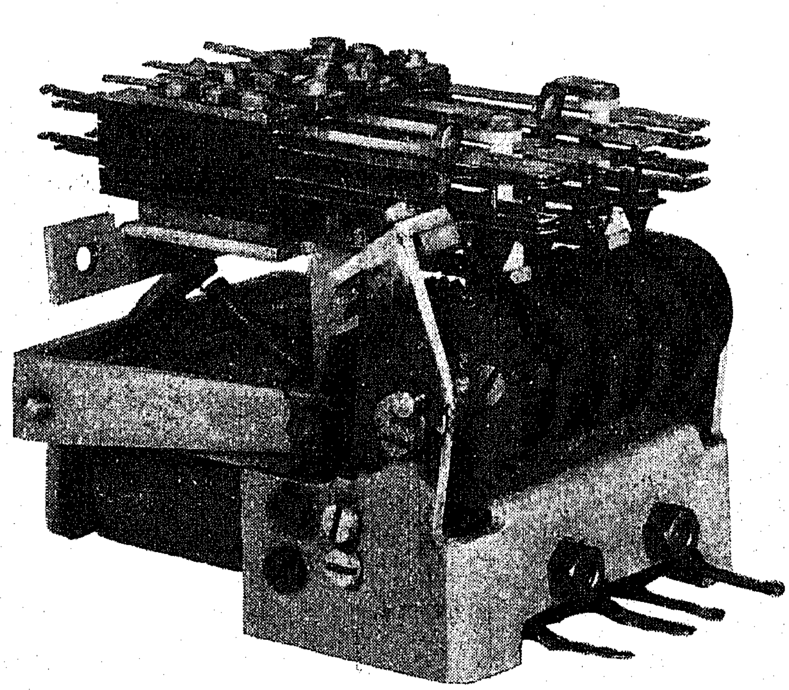

Fig. 2.—Stepping relay.

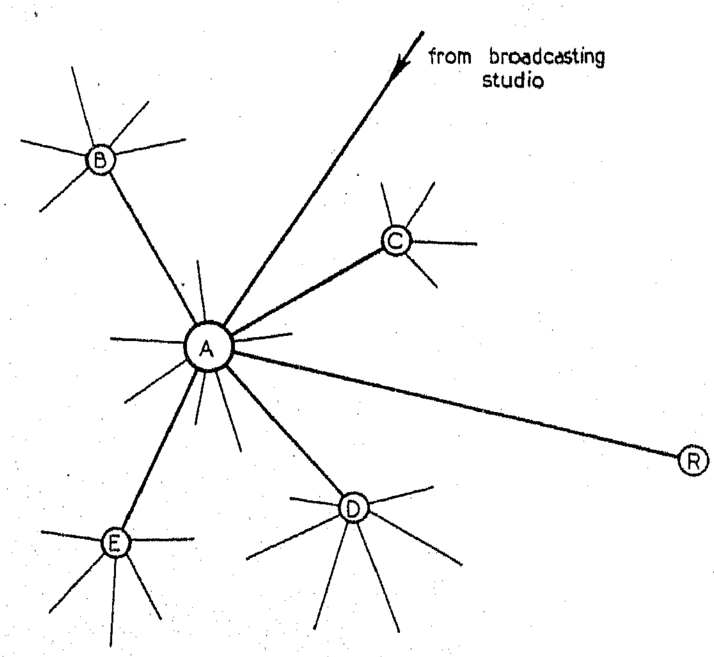

Fig. 3.—Layout of audio system for supplying programmes at loud-speaker strength.

A = central control, local amplifying and distributing station.
B, C, D, E = remote-controlled sub-amplifying and distributing stations
R = remote-controlled radio receiving station.

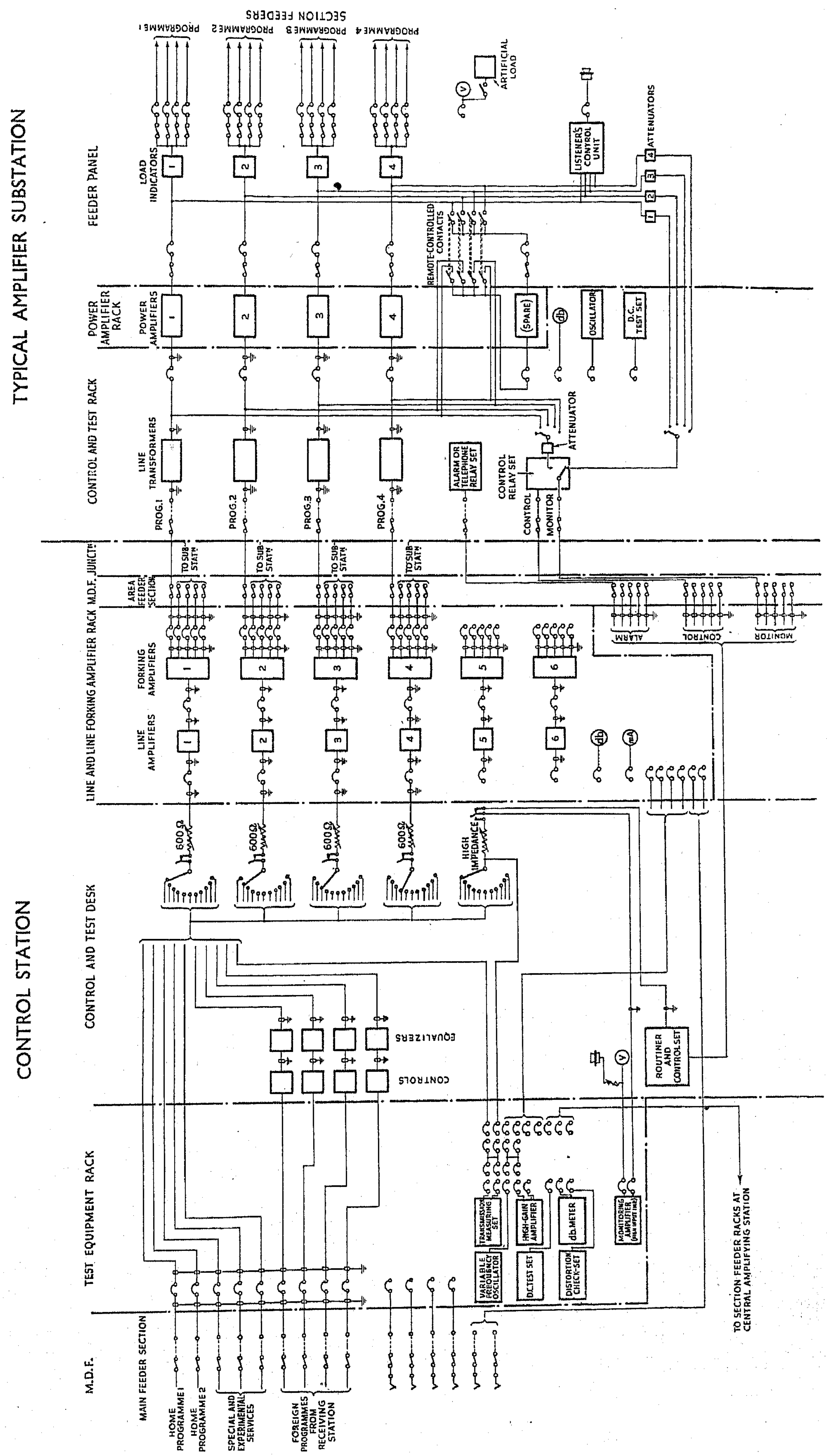

Fig. 4.—General trunking diagram. Audio-frequency wire broadcasting system.

home and foreign, is shown in Fig. 3. The system comprises a central control and amplifying station with several amplifying substations. Home programmes are fed from the regional broadcasting studios by suitable telephone pairs to the central amplifying station A. Distant programmes are received at the receiving station R and also fed to the station A. This latter, in addition to performing the function of a local amplifying station, is also the control station for the remote-controlled substations B, C, D, E, and the receiving station R. A trunking diagram for the system is shown in Fig. 4. It is not intended to describe in detail this system since it has not passed beyond the design stage. There are, however, several items in the system which have been tested out individually and which, possessing novel features, will therefore receive consideration.

Line Amplifiers

As shown on the trunking diagram of Fig. 4, the line amplifiers are in two stages; the first performs the function of an ordinary line amplifier specially designed for a wide frequency range, whilst the second, termed the "forking line amplifier," divides the programmes between the various amplifying substations. In a particular design the first line amplifier is capable of a gain of 42 db. and a signal/noise ratio of 62 db. at maximum gain. When the output is 150 milliwatts, the harmonic distortion products are 2 % at maximum gain. Negative feed-back, which can be adjusted according to gain requirements, is provided. The forking amplifier acts as a buffer between substation lines and so gives a measure of immunity from failure of programme to the remaining substations in case of breakdown of the line and line equipment associated with any one substation.

Main Amplifiers

In the earlier days of wire broadcasting the tendency was to install small amplifiers, adding others in parallel as the load increased. The output of individual units has progressively increased and at present amplifiers capable of giving an output of 2 kW are available. The requirements of an amplifier are much more difficult to achieve in a power amplifier than in a line amplifier. It is necessary to feed into a load varying over a wide range and, for high-quality reproduction, to have a flat amplitude/frequency response from about 50 to 7 500 c./s. The voltage regulation between full load and no load should preferably be such as not to give rise to an increase greater than about 25 %.

Distortion under all loading conditions should be less than 5 %, whilst noise has to be of low value.

The various requirements thus call for careful balancing of opposing factors.

By the use, in the final stage, of triode power valves in push-pull, by installing output transformers having high inductance, low leakage inductance, and low losses, and by applying negative feed-back, which improves both frequency response and regulation, the required result can be achieved without undue increase in costs.

Remotely Controlled Amplifying Substations

By the use of uniselectors and the application of the same technique as is used in automatic telephone practice, extensive facilities for controlling and monitoring unattended amplifying substations are possible for a capital expenditure on switching equipment and connecting cables equal to a small fraction of the total cost of the substations. Thus a considerable saving in labour charges can be effected. Any system of control must be such as not to introduce appreciable additional risks of failure. Since, however, certain standard relays used in telephone practice have contact-fault liability of the order of one in several millions of operations, the employment of these relays in a control and monitoring system ensures that the probability of failure is very remote.

In a particular scheme designed to control several substations from one central station, the following facilities were provided:

(1) Switching on the power supply for the main amplifiers for any one of four programmes.

(2) Switching on the power supply for the auxiliary amplifiers and connecting to any busbars according to the condition of the load.

(3) Disconnecting auxiliary amplifiers and connecting to another pair of busbars.

(4) Disconnecting auxiliary amplifiers from busbars and switching off power supply mains.

(5) Switching off the power supplies for the main amplifiers.

(6) Monitoring a particular programme from any substation.

(7) Applying routine monitoring continuously of all programmes at all amplifying stations.

(8) Observing the output load of the main amplifier in rotation.

(9) Giving alarm indications of the failure of the anode supply current.

(10) Giving alarm indications of failure of the anode supply relay during the working period of any amplifiers.

With regard to facility (7), use can be made of clock-controlled pulses at, say, $\frac{1}{2}$-minute intervals to actuate uniselectors at the central and controlled stations so that a sequence of programmes is monitored. Should any one programme be suspected, facility (6) can be brought into operation and prolonged observation made on the particular programme.

Remotely Controlled Receiving Station

In an ideal system of reception the local programmes would be transmitted to the central control station by cable direct from the broadcasting studios. For the reception of distant programmes a radio receiving station is generally needed. In some cases, however, direct cable connection is possible. The receiving station frequently has to be located a considerable distance from the central control station on a site reasonably free from various sources of electrical interference. On economic grounds it should be remotely controlled from the central station. The facilities to be provided might embrace the choice of any of several receivers, connecting the chosen receiver to the power supply, selecting a radio station, and providing indications at the control station that the receiver

is correctly functioning. Various schemes have been evolved and several have been tested out.

In one scheme several receivers are located at the receiving station, the number depending upon the number of programmes required simultaneously. For each

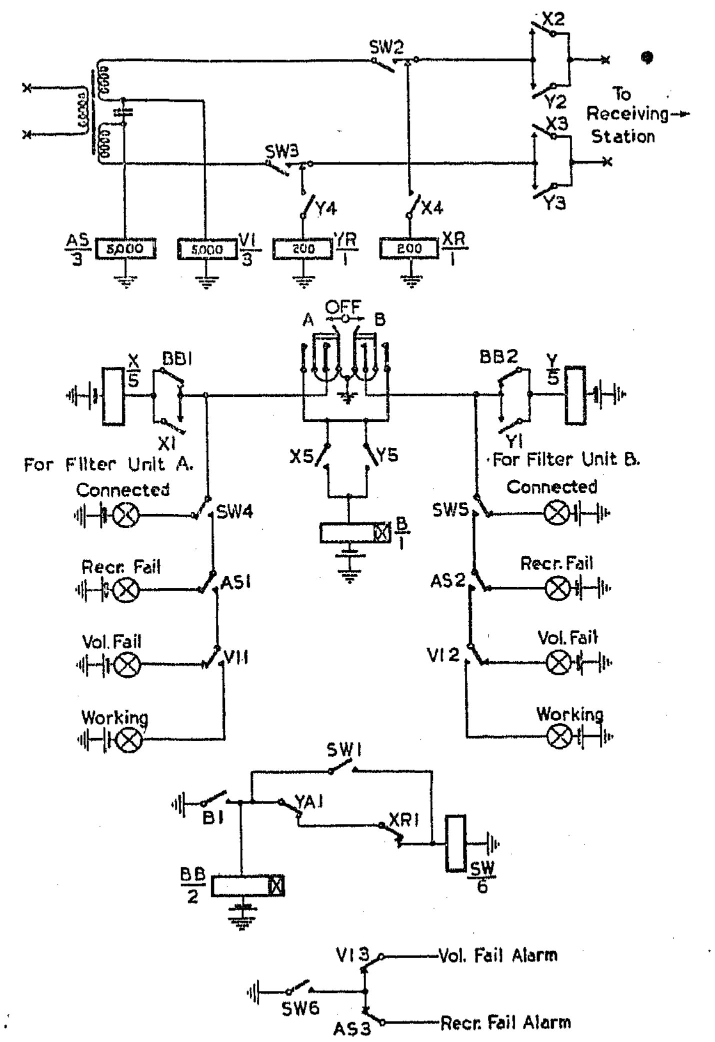

Fig. 5.—Remote control of radio receivers. Control system relay circuit. (For receiver relay circuit see Fig. 6.)

working receiver a cable pair is required. Associated with each receiver are two—or more—filter units designed to accept particular stations. A switch—A,B in Fig. 5—located on the control panel enables either the A or the B filter unit to be selected and connected to the associated receiver. By means of groups of relays, shown in diagrammatic form in Figs. 5 and 6, the following indications are given at the control station:—

(*a*) A failure of the receiver to function within a time period of ½ to 1 minute of switching on.

(*b*) A failure in the anode supply at any time during the operation of the receiver.

(*c*) A fall below a predetermined value of the strength of the rectified carrier of the received station, for a period of ½ to 1 minute.

The diagrams of Figs. 5 and 6 follow conventional telephone practice and are self-explanatory to those familiar with automatic working. It will be noticed that use is made of a facility available in telephone exchanges, namely an earth having a duration of 0·2 sec. made at 30-sec. intervals.

A second system of station selection, which is a modification of press-button selection principles, is illustrated in Fig. 7. At the central-station end is a switch S connected as shown to the contacts of a single-bank uniselector, whilst at the receiving station a two-bank uniselector with associated apparatus is located. If a particular station is required the arm of the switch S is turned by hand to the correct position, thereby earthing a contact on the associated uniselector. Relay A operates via C1 and the springs "dm." Relay B operates in parallel to the same earth over the line connecting the central receiver stations. A2 holds A, and B1 holds B. A1 operates C, A3 energizes the uniselector drive magnet coil DM (A), and B2 energizes the second uniselector drive magnet coil DM (B). Both uniselector armatures are attracted, the interrupter springs "dm" break, and both A and B are released. A1 releases C and the switch steps one contact. This operation is repeated until the marked contact is reached. On the last step, when both "dm" springs are broken and A and B are released, the wipers pick up the earth from the switch. C operates and at C1 prevents the re-operation of either A or B. The uniselector at the receiving end, having stepped round in unison with the uniselector at the central station, performs a function similar to the press-buttons in a direct-operated receiver

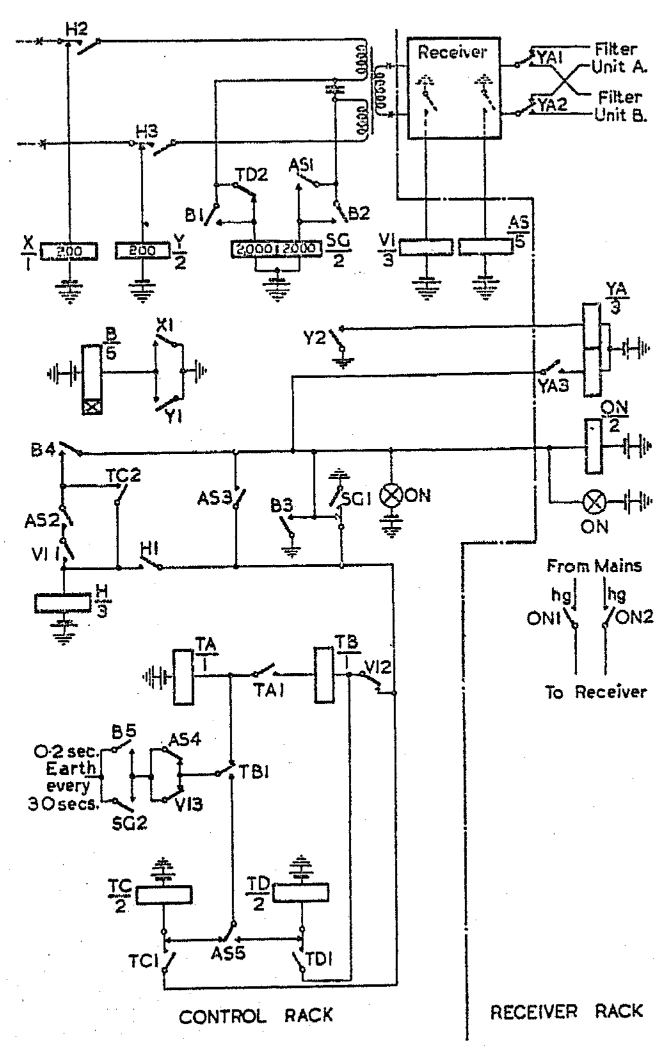

Fig. 6.—Remote control of radio receivers. Receiver station relay set. (For control relay circuit see Fig. 5.)

inasmuch as it enables the tuning motor circuit to be made and the motor to be rotated to select the particular station associated with a uniselector position. For fine tuning adjustment, the grid-bias voltage of a frequency-corrector valve is adjusted at the control station as

required. The control lines must be maintained at a voltage sufficiently high to overcome the effect of undesired interference voltages, the voltage of the grid of the corrector valve being reduced by a potentiometer. Frequency adjustment of several kilocycles in both the long- and medium-wave bands can readily be obtained by this method.

A third system of remote receiver control utilizes a variable-carrier-frequency transmitter over the connecting line between the control and receiving stations. At the latter station the carrier frequency, which can be varied between two defined limits, is multiplied in harmonic-producing equipment and the nth harmonic of the carrier frequency is selected by a band-pass filter, large—a necessary condition for single-span selection over a wide broadcasting spectrum—n must be large unless the carrier band $(f_2 - f_1)$ is large. However, since f_2 is limited by line attenuation the carrier band must necessarily be limited by the restrictions imposed upon f_2 unless line amplifiers and equalizers are used.

Harmonic selection of the carriers must therefore be made in several stages. Considering the general case, if each stage selects the nth harmonic of the previous stage and there are m such harmonic stages, the width of the final harmonic band is $n^m p = K$, where $p = f_2 - f_1$ and K is some predetermined value. For example, if it is desired to cover the whole of the broadcast medium-wave band, $K = 1\,000$ kc./s.

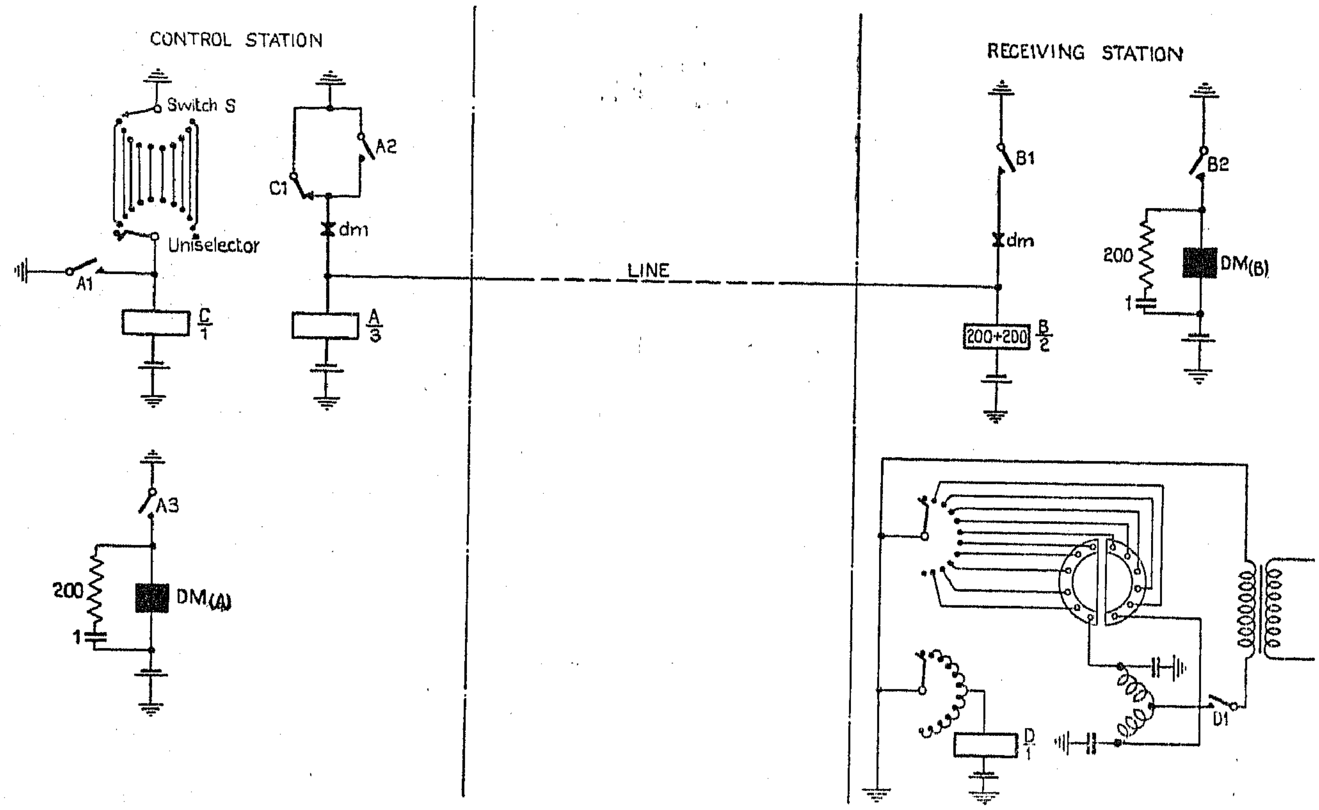

Fig. 7.—Receiver remotely controlled through uniselectors.

an essential condition being that none other than the nth harmonics of the extreme carrier frequencies are allowed to fall within the range of the band-pass filter. By varying the frequency of the carrier at the control station between the limits f_2 and f_1 a frequency variation between the limits nf_2 and nf_1 is available at the receiving end and takes the place of a beating oscillator in a superheterodyne receiver, the intermediate frequency being greater than the signal frequency. The obvious disadvantage of this type of receiver is the lack of high-frequency selectivity and its liability to produce intermodulation products. Furthermore, several stages of harmonic production and selection are needed to cover a wide station selection band, the number increasing with the width of the band and decreasing as the control carrier frequencies increase. For example, if the central carrier frequencies can increase from f_1 to f_2 the final harmonic filter must pass all frequencies between nf_1 and nf_2. If a single translation were affected, a necessary condition would be that $(n+1)f_1 > nf_2$, that is $f_2 < f_1 + \frac{1}{n}f_1$. In order that the final harmonic band $n(f_2 - f_1)$ shall be

Now the $(n + 1)^m$ harmonic of the lowest controlling frequency must lie outside the final harmonic band needed for station selection, i.e.

$$(n + 1)^m f_1 > n^m f_2 \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

$$\text{and } (n + 1)^m f_1 - n^m f_1 > K \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (2)$$

From (1) and (2) and the fact that the final harmonic frequency band extends from $n^m f_1$ to $n^m f_2$ the relationships existing between the various quantities, on the assumption that a harmonic frequency band of 1 000 kc./s. is required, have been deduced and are shown in bar graphs in Fig. 8. As an example of their use, suppose second harmonics were selected in 5 stages (A). This would necessitate carrier frequencies varying between 62·5 and 93·75 kc./s. for a harmonic frequency change from 2 000 to 3 000 kc./s. If, however, the third harmonic were selected in 5 stages (B), the carrier frequencies would vary from 12·34 to 16·46 kc./s. approximately, whilst the harmonic frequency would change from 3 000 to 4 000 kc./s. It might be decided that 5 stages were too many and that a change of carrier frequency of 4·12 kc./s. was too small. A three-stage selection would remedy both

defects but might raise the carrier frequencies to values too high for the particular line in use.

A three-stage selection of fourth harmonics (C) might be a useful compromise. The final selection depends on the length and characteristics of the connecting line between the control and receiving stations.

require amplification. For this purpose a broad-band amplifier can be fixed at the base of the aerial and switched into circuit by means of either a time switch or a remotely operated relay. Repeater circuits can be used where the line attenuation is too great for one amplifier.

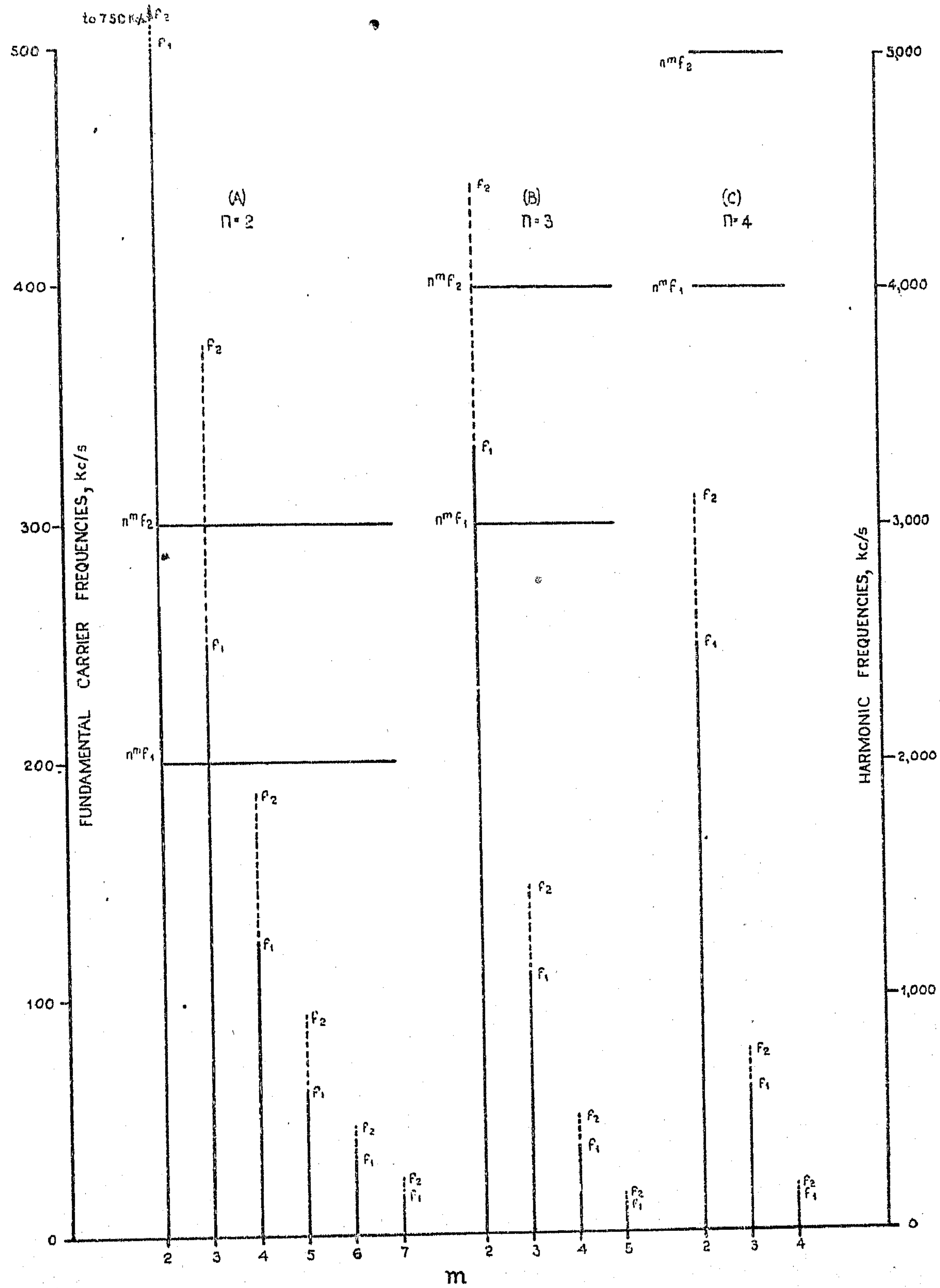

Fig. 8.—Relationship between harmonic frequency band and fundamental carrier band for various stages of harmonic multiplication.

n = harmonic selected in each of m stages.
nmf_1 and nmf_2 = final harmonic frequencies of carrier frequencies f_1 and f_2.

When a suitable receiving site can be obtained within 1 or 2 miles of the central control station, economies can be effected by housing the receivers in the same building as the power amplifiers, and making connections to the remotely located aerial by means of a cable pair. The attenuation of the pair will normally be such as to

Underground Distribution

At the present time in Great Britain the system in general use employs an overhead open-wire distributing network with teed connections from common feeders to the individual listener's loud-speaker selecting switch. Usually two programmes are provided. The chief ad-

vantage of the overhead open-wire distribution over an underground cable system is the relatively low capital costs and the ease with which subscribers can be connected. Apart from aesthetic considerations, the advantages of the underground system are longer life and greater freedom from fault liability. Cables laid directly in the ground or running in ducts may be used. When ducts can be shared with other services the mutual economic advantage might be very appreciable; in fact in such a case the difference between the annual charges of the overhead and underground wire broadcasting installations might be negligible.

The selection of suitable underground cables for distribution purposes requires careful consideration. The problem of distribution has features common to electric power and telephone work. On the one hand it is necessary to have a cable that can readily withstand peak voltages of the order of those used for local distribution of electricity, while on the other hand it is required to transmit a broad band of frequencies—up to 7 500 c./s.—with reasonably level response.

In the design of a particular underground system an average peak voltage of 120, with occasional peaks much higher than 120, was visualized.

The use of this comparatively high voltage on the listener's distributing network is due to economic considerations; the higher the voltage the less the size of copper conductor required, for a given energy loss. Since, however, the impedance of the moving coil of most modern loud-speakers is only a few ohms, a large step down in voltage is needed before connection is made to the loud-speaker.

Cables

The frequency requirements place a limit upon the permissible capacitance of the cable; the voltage stipulation necessitates the use of dielectrics that unfortunately have a dielectric constant (permittivity) considerably greater than unity. Happily the individual lengths of line required in a local wire broadcasting distributing network are not great. It is thus possible to use cables having capacitances of $0 \cdot 1$ to $0 \cdot 2\,\mu$F per mile, according to the degree of impregnation. A paper cable impregnated with petroleum jelly or a suitable oil has several advantages, and tests made on such cables have shown that their resistance to moisture penetration is very high. This fact has considerable economic value since it removes the necessity of sealing the ends of service feeders terminated at a control box in the listener's premises.

Tests were made to determine:—

(1) The extent to which water penetrates into the cable when the lead sheath is punctured.

(2) The effect upon insulation resistance of leaving the open cable-end exposed to the atmosphere.

(3) The values of cross-talk.

(4) The attenuation over a wide frequency range under various conditions of loading.

Brief particulars of the cables are given in Table 1.

Short samples of cable each with an open end were placed in water for 48 hours with a coverage of approximately 2 in., the cable being bent so that one end was clear of the water. The effects noted are given below.

Cable A.

After the lead had been cut back 3 in. from the open end the insulation resistance was found to be <2 MΩ. The papers were quite wet for this distance. Upon cutting back 6 in. and fanning out the wires, the insulation resistance rose to $>1\,000$ MΩ but there was definite evidence of moisture in the papers for a distance of 4 in. from the original open end.

Cable B.

After the lead had been cut back for 6 in., the insulation resistance was 2 MΩ and the papers were quite wet. When the lead was cut back 9 in. the insulation resistance rose to approximately 1 000 MΩ, but beads of moisture were to be seen 15 in. from the original end.

Cable D.

It was noted, after cutting back the lead 4 in., that although the insulation resistance was $>1\,000$ MΩ and the cottons dry, the lapping tapes were thoroughly wet.

Cables C and E.

After the lead had been stripped back 1 in. the insulation resistance was nearly infinitely high on both samples, there being no sign of moisture on the papers excepting at the extreme ends where they had actually been in contact with the water.

In the light of these results it was decided to immerse Cables C, D, and E for a longer period with approximately 2 in. coverage of water. The following observations were made after 9 days.

Cable D.

The cottons were wet for a distance of 2 in. from the open end, but after the wires had been opened out for this distance the insulation resistance was about 1 000 MΩ. Further investigation showed, however, that the tapes were quite wet up to 10 in. from the end.

Cables C and E.

Upon stripping the lead 1 in. from the cable end, some signs of moisture were noted in the papers, and the insulation was <2 MΩ. When the lead was cut back a further 2 in., however, it was observed that moisture had not penetrated to a distance greater than 1 in. from the end, and the insulation resistance rose to much more than 2 000 MΩ.

A final test was made on Cable C by immersing it for 68 days in water with a coverage of 3 in. At the end of this period, when the lead sheath had been slightly cut away from the end the lowest insulation resistance of any pair to the other bunched pairs and sheath was about 2 MΩ. Cutting back the lead sheath to a distance of 4 in. resulted in an increase to 6 MΩ, whilst a removal of 6 in. of lead caused an increase too high for measurement, i.e. the insulation resistance was several thousand megohms. With regard to the tests on open-ended cables exposed to the atmosphere, samples of cables were placed in an outside position and their ends laid open for a distance of 4 in. The cables were not subjected to direct effects of the rain and were sheltered from the sun. Tests made during a period of 1 month, during which there were heavy rains, yielded the following minimum in-

Table 1

PARTICULARS OF LEAD-COVERED 4-PAIR CABLES

Reference	Description	Primary constants (per mile), in ohms, henrys, mhos and microfarads			
			200 c./s.	1 000 c./s.	2 000 c./s.
A	Impregnated paper core, screened, 4 pairs, 40 lb. per mile, each pair twisted and lapped with one layer of plain paper and one layer of metallized screening paper. Two outer lappings of paper, then lead sheath. Paper impregnated with a resin oil and dried previous to lapping. External diameter 0·65 in.	Resistance Inductance Leakance Capacitance	40·8 0·00098 $0 \cdot 9 \times 10^{-6}$ 0·094	40·8 0·00102 $5 \cdot 0 \times 10^{-6}$ 0·095	42·7 0·00092 $68 \cdot 0 \times 10^{-6}$ 0·088
B	Impregnated paper core, screened, 4 pairs, 40 lb. per mile. Similar to A, but paper impregnated after lapping and partially drained. External diameter 0·635 in.	Resistance Inductance Leakance Capacitance	40·0 0·00093 $0 \cdot 14 \times 10^{-6}$ 0·104	40·4 0·00105 $3 \cdot 18 \times 10^{-6}$ 0·092	48·0 0·0012 $80 \cdot 0 \times 10^{-6}$ 0·11
C	Impregnated paper core, enamelled, screened, 4 pairs, 40 lb., each wire enamelled and covered with two layers of paper. Each pair twisted together and lapped with one layer of metallized screening paper. Two outer lappings of paper, then lead-sheath cable impregnated with petroleum jelly. External diameter 0·575 in.	Resistance Inductance Leakance Capacitance	43·6 0·00103 $0 \cdot 62 \times 10^{-6}$ 0·170	43·1 0·00101 $5 \cdot 69 \times 10^{-6}$ 0·174	47·0 0·00094 $67 \cdot 0 \times 10^{-6}$ 0·171
D	Enamelled and double-cotton-covered, waxed and screened, 4 pairs, 40 lb. per mile, each wire enamelled and double-cotton-covered. Each pair twisted together and covered with one lapping of linen tape and one lapping of metallized screening paper, one outer lapping of stout linen tape, cable impregnated with paraffin wax. External diameter 0·626 in.	Resistance Inductance Leakance Capacitance	43·6 0·00084 $0 \cdot 32 \times 10^{-6}$ 0·20	43·5 0·0010 $0 \cdot 45 \times 10^{-6}$ 0·20	43·3 0·0010 $52 \cdot 0 \times 10^{-6}$ 0·20
E	Paper-core twin distributing telephone cable, 4 pairs, 10 lb. per mile, each wire covered with one lapping of paper and twisted into pairs. No screening. Two outer lappings of paper, then lead-sheath cable impregnated with petroleum jelly. External diameter 0·32 in.	Resistance Inductance Leakance Capacitance	167·0 0·0010 $0 \cdot 40 \times 10^{-6}$ 0·12	167·0 0·0010 $3 \cdot 8 \times 10^{-6}$ 0·11	171·0 0·00097 $14 \cdot 6 \times 10^{-6}$ 0·11

sulation-resistance figures: A >2 000 MΩ, B 240 MΩ, C too high for measurement, D 180 MΩ.

The tests confirmed the conclusion, already drawn from the immersion tests, that from the point of view of moisture penetration the C cable, impregnated with petroleum jelly, was superior to the other cables. Cross-talk tests were made by terminating the pairs in 600 Ω resistance and measuring the relative values of the voltages across the disturbing and disturbed pairs. Tests were made with all pairs balanced and also with either wire of the disturbing pair connected to earth. The minimum requirements were 85 db. per 1 000 yards in the balanced condition and 75 db. in the unbalanced. Cables A, B, and C met these conditions, but as Cable D was considered unsatisfactory from the moisture-penetration aspect it was not tested.

The results on a ½-mile length of Cable C in a balanced condition were as follows:—

Frequency 5 kc./s., cross-talk 95 db.
Frequency 10 kc./s., cross-talk 78 db.

Cable E.

A 560-yard length of an ordinary unscreened 10-lb. telephone cable impregnated with petroleum jelly gave values of cross-talk of 70 db. and 54 db. respectively, under balanced and unbalanced condition at a frequency of 5 kc./s., whilst for a ½-mile length of 10-lb. cable similar to Cable C, but without screening, the values were 79 db. and 58 db. The addition of screening to this latter 10-lb. cable increased the cross-talk values to 103 db. and 91 db.

One of the most important requirements in a wire

broadcasting system is to ensure that the cables do not introduce undesirable variations of attenuation with varying frequencies. The load varies within wide limits, and this fact complicates the problem of equalizing over a wide band of frequencies. Tests showed that the most effective way of obtaining level amplitude/frequency response was to equalize each loud-speaker circuit at the listener's end and to make the combined termination approximately resistive. Some guidance in this matter can be gained from theoretical considerations. It is required to examine the manner in which the ratio of the input feeder voltage at the amplifying station to the voltage at the load varies over the frequency range.

extent to which it is possible to equalize the impedance of a loud-speaker unit over a wide audio band is shown in Fig. 9. It will be observed that the equalized circuit may be regarded as resistive over a large range of frequencies. A certain standard loud-speaker unit had an average value of impedance equal to 15 000 ohms, and this has been taken in preparing the curves of Fig. 10, which show the voltage-drop for various terminating loads on 1 mile of 40 lb.-per-mile cable, Class C, Table I, having the impedance characteristics shown in Fig. 11.

It will be seen that theoretically the attenuation at any particular load is substantively constant over a large range of frequencies. To confirm theoretical expectations

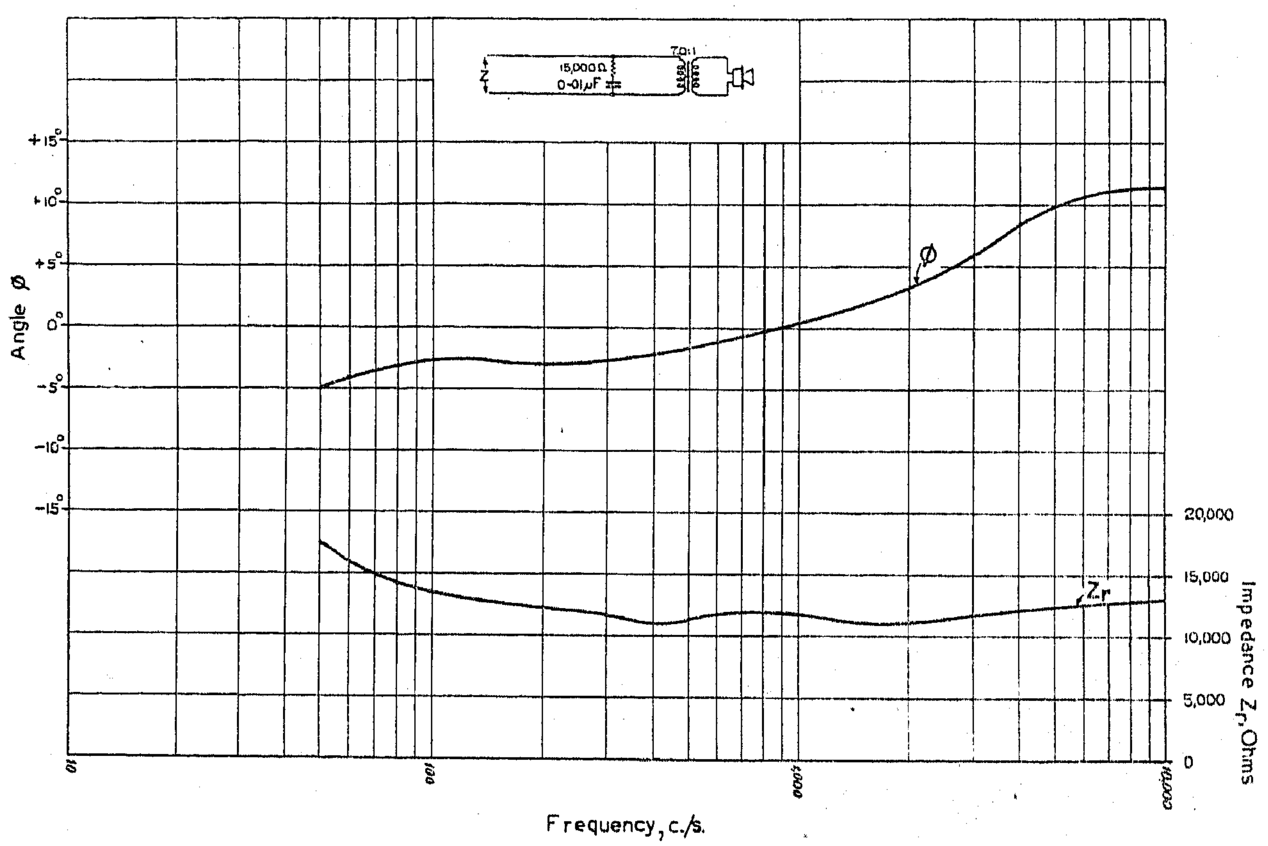

Fig. 9.—Impedance measurements of loud-speaker with 70 : 1 ratio transformer, equalized as shown.

Now the voltage V across a line of length l at a distance x from the sending end is obtained from the expression

$$V = V_s \frac{\sinh P(l-x) + \frac{Z_r}{Z_0}\cosh P(l-x)}{\sinh Pl + \frac{Z_r}{Z_0}\cosh Pl}$$

where V_s = sending-end voltage,
Z_r = terminating load impedance,
Z_0 = line characteristic impedance.

Thus it follows that

$$\frac{V_r}{V_s} = \frac{\frac{Z_r}{Z_0}}{\sinh Pl + \frac{Z_r}{Z_0}\cosh Pl}$$

where V_r/V_s is the ratio of received to transmitted voltage.

Now the value of Z_r can be made substantially constant over a wide frequency-band for a particular number of loud-speakers constituting the terminating load, but the value of Z_0 decreases with increase of frequency. The actual tests were made. For this purpose the input voltage to the cable was kept constant and the output voltage across the terminating load measured. The calculated and measured results are in close agreement, as shown in Fig. 10. Since the impedance equalization is such as to cause each loud-speaker load to act substantially as a constant resistance over the whole frequency band, the volume control does not affect the frequency/acoustic-response characteristic.

Listener's Control Unit

Two facilities are required in the listener's premises; selection of programme and adjustment of volume. Control of volume to the extent of 20 db. can conveniently be obtained by the use of resistors, preferably placed in the high-voltage side of the loud-speaker transformer since in this position variation in rheostat contact resistance has little effect. It is convenient to the listener to have the two controls close together. Furthermore, there is some advantage in having the loud-speaker transformers housed in the same case as the selector and

volume-control switches, since by so doing dangerous voltages are removed from the loud-speaker.

A circuit diagram showing one arrangement of the

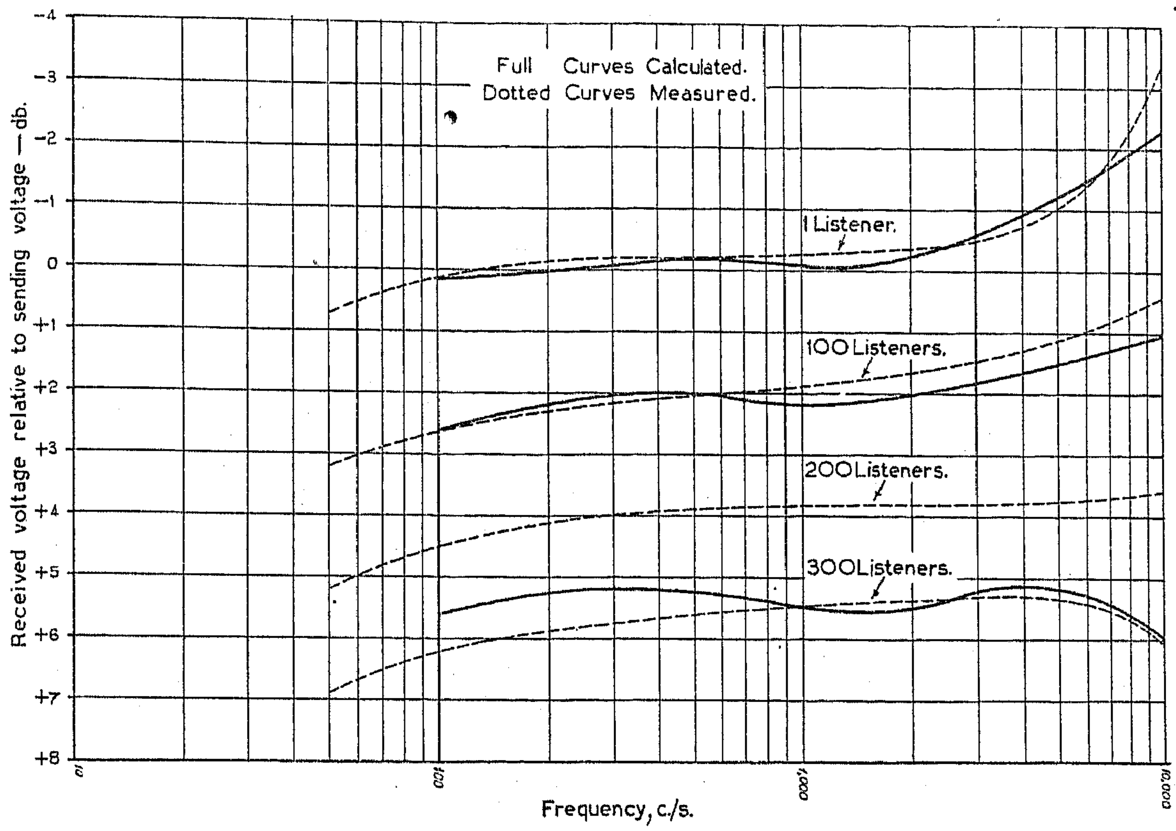

Fig. 10.—Voltage drop over 1 mile of cable, Class C, Table 1, terminated in various loud-speaker loads. Each loud-speaker unit assumed to have a resistance equal to 15 000 ohms, measured across the primary of the loud-speaker transformer.

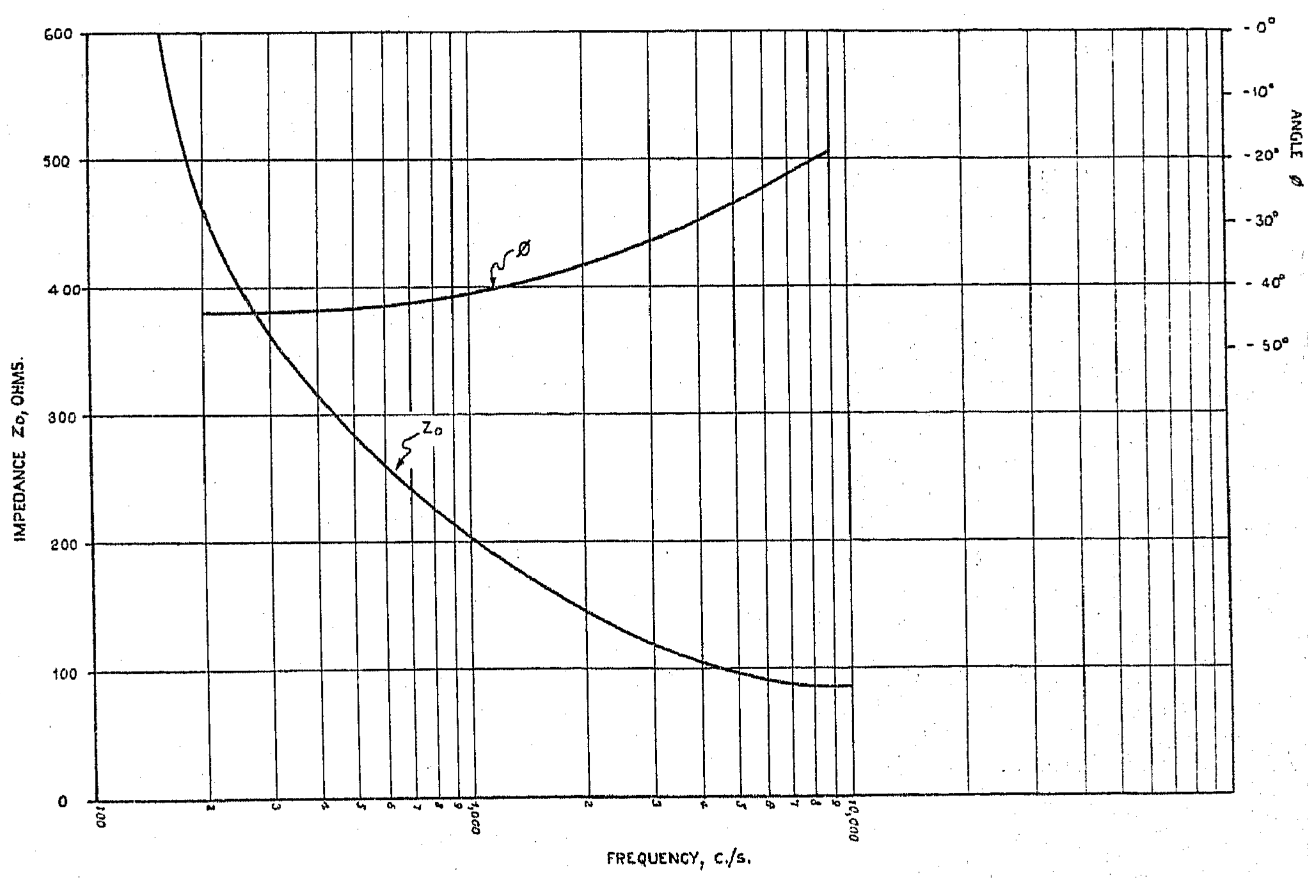

Fig. 11.—Characteristic impedance of 40-lb./mile cable, Class C, Table 1.

listener's selector and control unit is shown in Fig. 12, whilst a photograph is given in Fig. 13.

The service cable terminates directly in the control unit, no sealing being required (as already explained in the section on cables).

Loud-speakers

Probably the weakest link in the chain of equipment between speaker and listener is the loud-speaker. Admittedly, great improvements have been made in recent years, but the average standard of reproduction is still not high. A contributing factor to this state of affairs is the fact that most listeners have no very decided views regarding the question of quality and will accept stan-

dards of reproduction which to the sensitive or trained ear are quite unacceptable. However, even this class can be educated to appreciate good quality, and there is little doubt that in time general appreciation of good-quality reproduction will increase.

A marked contribution towards improvement in loud-

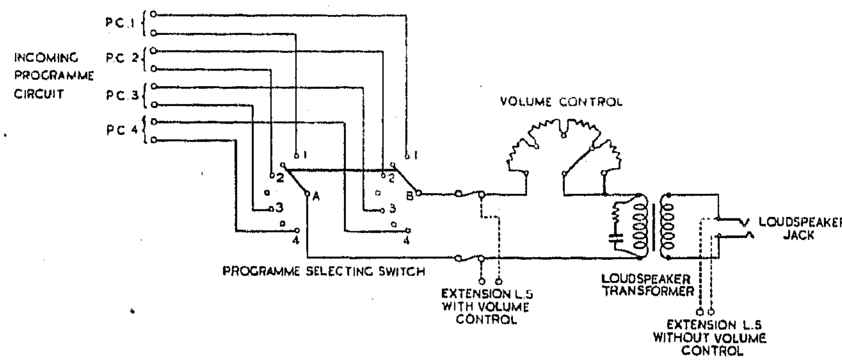

Fig. 12.—Circuit of listener's programme control unit for audio-frequency system (see Fig. 13).

speakers has been made by the Post Office engineers W. West and M. McMillan.[3] In the loud-speaker developed by these engineers the ideal striven after is a uniform increase in sound pressure on the axis of the diaphragm with rising frequency, over part of the frequency band from 100 to 4 000 c./s., at a rate of 2·5 db.

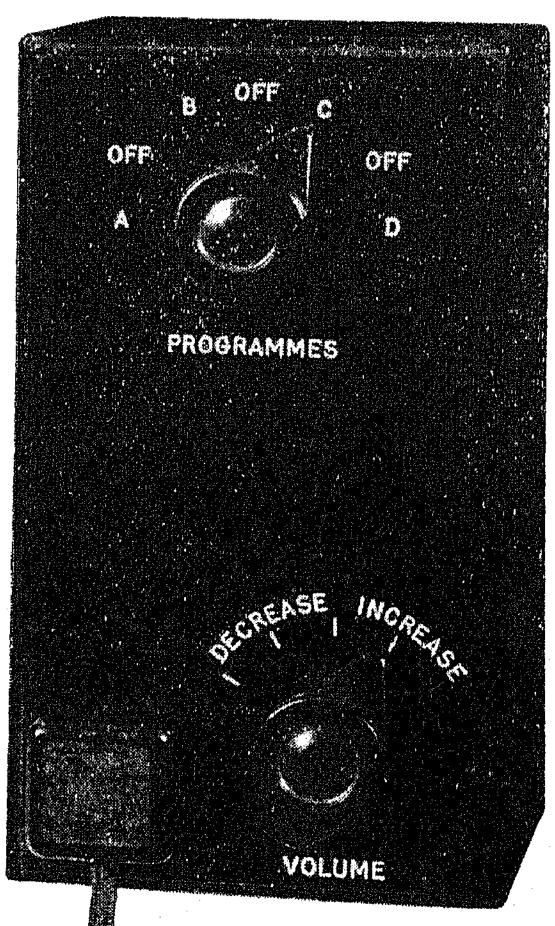

Fig. 13

per octave. Such a response characteristic for a loud-speaker in an ordinary living-room gives more natural reproduction than a level response, since it recognizes and makes some allowance for the varying degree of absorption and reflection of the walls of the room with frequency. For the reduction of air resonances within the case, the loud-speaker box is completely closed and effectively lined; a combination of felt, lead sheet, and corrugated paper being used as shown in Fig. 14.

PART 2. WIRE BROADCASTING AT CARRIER FREQUENCIES

The chief attraction of carrier systems of distribution lies in the fact that existing electricity-supply or telephone networks can be utilized, with a consequent saving in line plant costs. P. P. Eckersley and his associates have already carried out a considerable amount of experimental work in England and abroad on carrier distribution over power networks, but the author has no detailed information regarding their tests. The fact that the electricity supply networks in Great Britain are connected to a larger number of premises than the telephone networks constitutes the chief advantage of their utilization for distribution of programmes at carrier frequencies, but this advantage has its limitations.

Carrier over Electricity Supply Feeders

In considering the application of carrier currents to either electricity supply mains or telephone lines, it is desirable to have a clear conception of each type of distribution system. In the old system of d.c. distribution of electricity a whole district or town was supplied from one central point, all feeders being connected in parallel. The wire network in a medium-sized town or a large area of a bigger town might thus be solidly connected together, feeders extending 2 miles or more from the supply station. With the greatly extended use of a.c. supplies this type of system is becoming rare and the modern system utilizes high-voltage cables to feed main and auxiliary substations, the latter serving comparatively small areas. In some cases street transformers feeding small groups of consumers are used. Thus with the old system the whole of the electricity supply network would have to be energized at carrier frequencies even though only a few listeners were connected. The attenuation at the extreme end of the system would be so great and the noise voltages so high that the voltage of the carrier at the sending end to ensure good-quality reception would be impossibly high, in some cases approximating to that of the electricity supply. Again, on modern systems the number of substations is considerable and as the loss experienced in bridging transformers is high, it would be preferable if not obligatory to connect the carrier amplifiers to the low-voltage side of each transformer, thus necessitating a large number of amplifiers. A telephone network, unlike a power network, comprises individual pairs to connect each subscriber to a central position. Furthermore, the attenuation per mile is not so great on telephone pairs as on electricity supply mains. Four facts follow in favour of the use of underground telephone pairs in preference to underground electricity supply mains:—

(1) Energizing of subscribers' lines can be effected as and when required.

(2) Fewer carrier amplifiers are needed.

(3) Noise arising from terminal equipment can be reduced to small dimensions by inexpensive filters. (It is

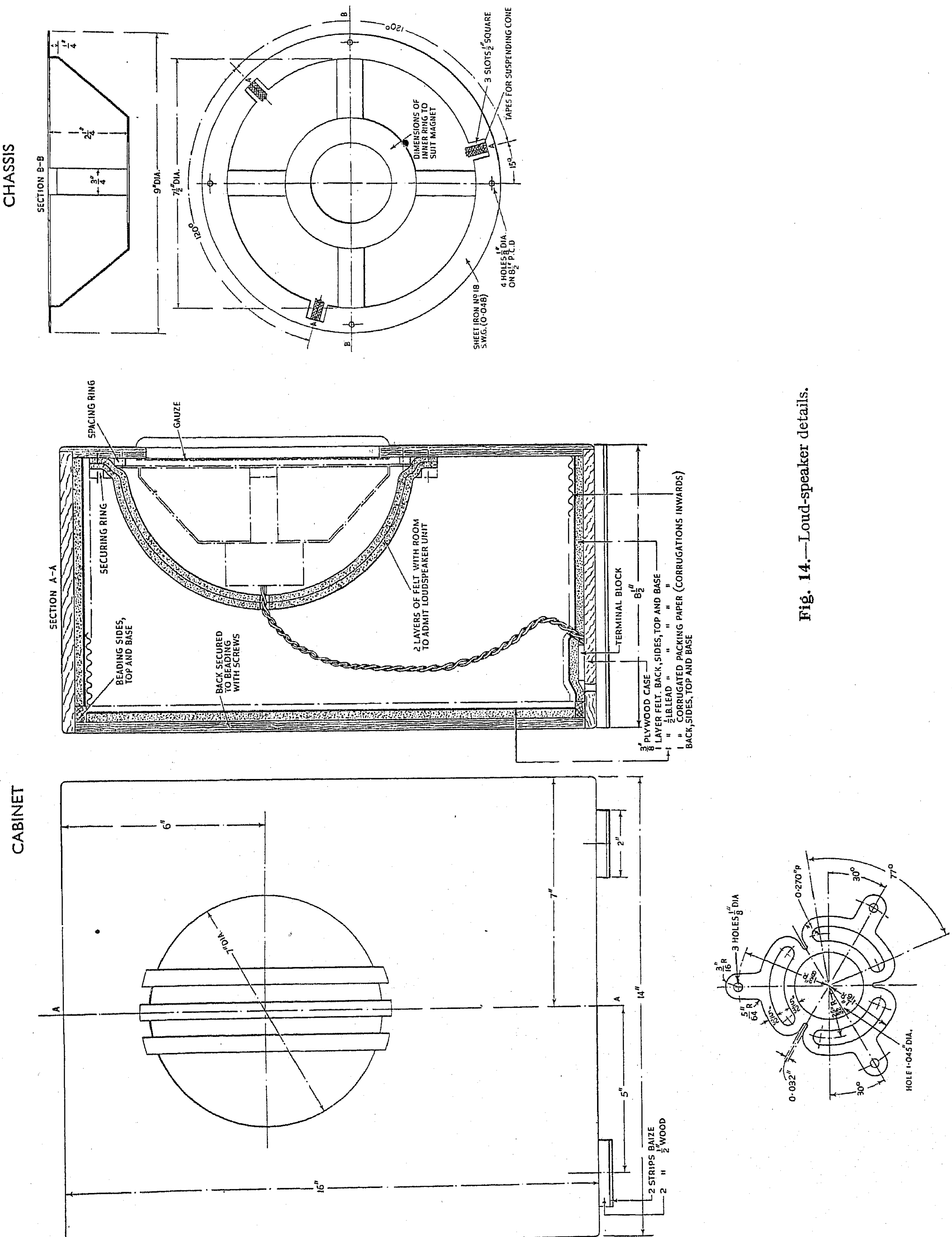

Fig. 14.—Loud-speaker details.

hardly practicable to insert filters in the electricity service feeders of non-subscribers).

(4) A considerable saving in power can be effected, owing not only to the lower line attenuation but also to the lower noise-level.

It is difficult to generalize regarding the carrier power required for transmission over power lines, but some average values based upon a large number of tests on several substation distribution systems at frequencies within the long-wave radio broadcasting band are of interest and are shown in Fig. 15. In preparing the curve it was assumed that the limiting factor is signal-to-line noise ratio at the consumer's premises. Actually the limitation in many cases was low signal strength at the receiver end, particularly at the higher carrier frequencies. Furthermore, only average values of attenuation and peak noise have been taken. Here again the curve errs on the side of leniency, since it was found that both attenuation and noise varied considerably with time. Finally, the carrier voltages were measured either at street pillars or across the fuses of consumers' mains. Thus the effect of internal wiring was disregarded, although in many cases losses of the order of 10 db. were measured. With these reservations it will be seen from Fig. 15 that if a carrier input of 10 watts (corresponding to a voltage of 11 volts) had been provided at the substations considered, a signal/noise ratio of 40 db. at the entry of the consumer's premises would have been obtained in 93 % of the cases.

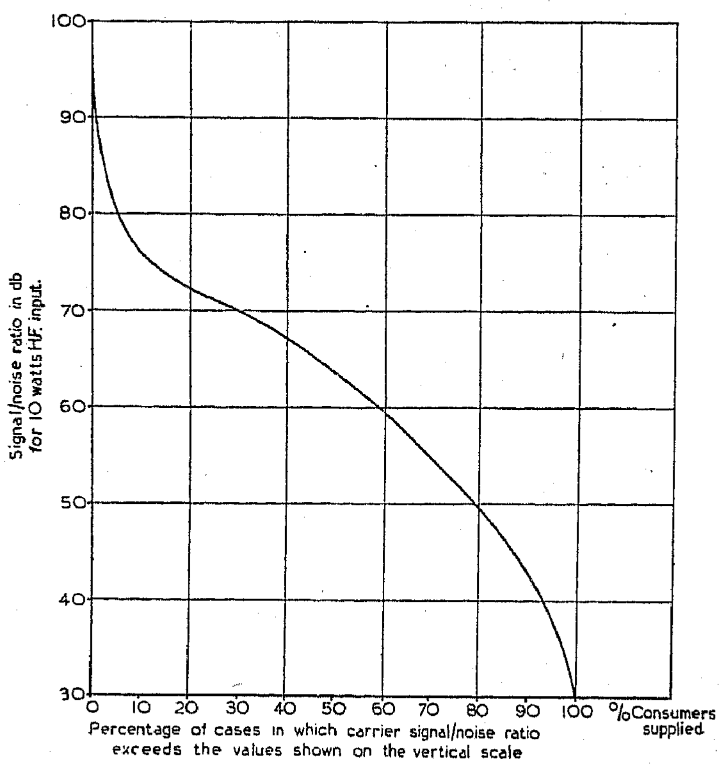

Fig. 15.—Signal/noise ratio on electricity supply mains for 10 watts input at frequencies within the radio broadcasting long-wave band.

The substation feeders concerned extended to an average distance of 0·6 mile from the substation, and generally the cables were 4-core of three sizes having sectional areas of conductor equal to 0·1, 0·2 and 0·3 sq. in. respectively. The average number of consumers per substation was 612, giving a rough value of 16 milliwatts per consumer of carrier power to provide an average value of signal/noise of 40 db. in 93 % of the cases. As will be shown later, this value of carrier power is very much higher than is needed when telephone pairs are used. Moreover, it should be stressed that average values are not a criterion of satisfactory service. The carrier power needed to render innocuous the fluctuations in signal/noise ratio might exceed the above values many times. However, the noise volume differs considerably according to the type of load, and in some areas comparatively quiet circuits exist.

Provided line noise is not the limiting factor in a carrier system, the signal carrier power required at the line terminal equipment to which a receiver is connected is less than 1 microwatt.

Carrier over Telephone Pairs—Power Required

Tests made on telephone lines comprising underground pairs with cable connections—drop wire—from distribution points have shown that 1 microwatt of modulated carrier power is usually sufficient for a satisfactory service free from interference.

To find the amount of power necessary to feed a given area by carrier, consider the case of a subscriber fed by an individual line of length r, having amplifiers spaced l along the line. Now, assuming that the whole amount of carrier power p_i available at the subscriber's receiver is applied to the input circuits of his receiver, and that this is equal to the input carrier power of each line amplifier, the total carrier power per subscriber's line under ideal conditions when r/l is a whole number $= \frac{r}{l} p_i e^{2\alpha l}$.

The value of this expression, and thus of the power, is a minimum when $1/l = 2\alpha$. The expression for minimum power therefore becomes $rp_i 2\alpha e$ per line. If the distribution area is circular and lines radiate from a centrally placed transmitter, the total power required by the transmitter is

$$\frac{2}{3}\frac{Rp_i N 2\alpha e}{\eta} = \frac{2\pi R^3 p_i n 2\alpha e}{3\eta}$$

In this expression the terms have the significance given at the beginning of the paper and α is measured in nepers. Thus, assuming that the line attenuation α is 1·0 neper per mile and that each receiver requires 1 microwatt input carrier power, the minimum carrier required to feed an area having a radius of 20 miles and a telephone density of 500 subscribers per square mile is approximately 45 watts. With a transmitter efficiency as low as 1%, the total minimum low-frequency power required to supply over 600 000 subscribers is less than 5 kW. Owing to the very large number of amplifiers required the above scheme is quite impracticable. Only by an exact examination of the various factors in actual areas can a valid estimate of power and other requirements be obtained. Such an examination would take account of population distribution and actual run of cables. However, an approximation to the actual conditions may be obtained by considering the power required to feed subscribers located uniformly in a circular area of varying radius R_a. At the centre of the area an amplifying station is situated to supply carrier power via lines radiating to each subscriber.

The total carrier power needed for each local area is $p_i n \sum_{r=0}^{r=R_a} 2\pi r \delta r e^{2\alpha r}$, which expression, provided n is large enough and the subscribers' premises are uniformly spaced, has an integral value

$$p_i n 2\pi \left[\frac{e^{2\alpha R_a}}{2\alpha}\left(R_a - \frac{1}{2\alpha}\right) + \frac{1}{4\alpha^2}\right] \text{ (approx.)} \quad . \quad (3)$$

Thus the ratio between the average carrier power supplied to each line and the input power of each receiver is obtained by dividing expression (3) by $p_i \pi R_a^2 n$, giving a ratio

$$\frac{2}{R_a^2}\left[\frac{e^{2\alpha R_a}}{2\alpha}\left(R_a - \frac{1}{2\alpha}\right) + \frac{1}{4\alpha^2}\right] \quad . \quad . \quad . \quad (4)$$

Curves showing the value of expression (4) for varying values of R_a are given in Figs. 16 and 17. The lowest curve of Fig. 16 applies approximately to overhead lines, whilst Fig. 17 is more applicable to underground cables.

To give some idea of the order of magnitude involved Table 2 has been prepared, showing the carrier power required to feed various numbers of receivers uniformly distributed around a centrally placed amplifier.

In the final column of Table 2 the input requirements are shown as 1 microwatt in the case of underground cables and 25 microwatts in the case of overhead circuits, the larger figure in the latter case being due to the greater input level needed to overcome the greater unwanted pick-up of the open-wire lines.

The two outstanding features of the curves of Figs. 16 and 17 and the figures of Table 2 are firstly the small amounts of carrier power required to supply a large number of suitably located subscribers, and secondly the rapid increase in this power as the distance from the central amplifier increases beyond a value depending upon the feeder attenuation.

In practice the size of the local distributing area supplied by a final power amplifier is determined by the size of the existing telephone distribution area, but ignoring this consideration it is instructive to investigate the manner in which the power requirements of a large district divided into a number of smaller distribution areas depend upon the size of these individual distribution areas.

The hypothetical case of a large district of 50 miles radius having 1 million potential subscribers has therefore been considered. The district has been regarded as being divided up into a large number of equal areas each having a value equal to $(4/3)\pi R_a^2$, where R_a is the radius of the centre distributing area. The equivalent radius of each area has been taken as $\sqrt{(4/3)}\ R_a = 1\cdot 15 R_a$ in order to apply expression (4).

It is realized that this method of computation is approximate. However, it enables some idea to be formed of the order of magnitudes involved. For

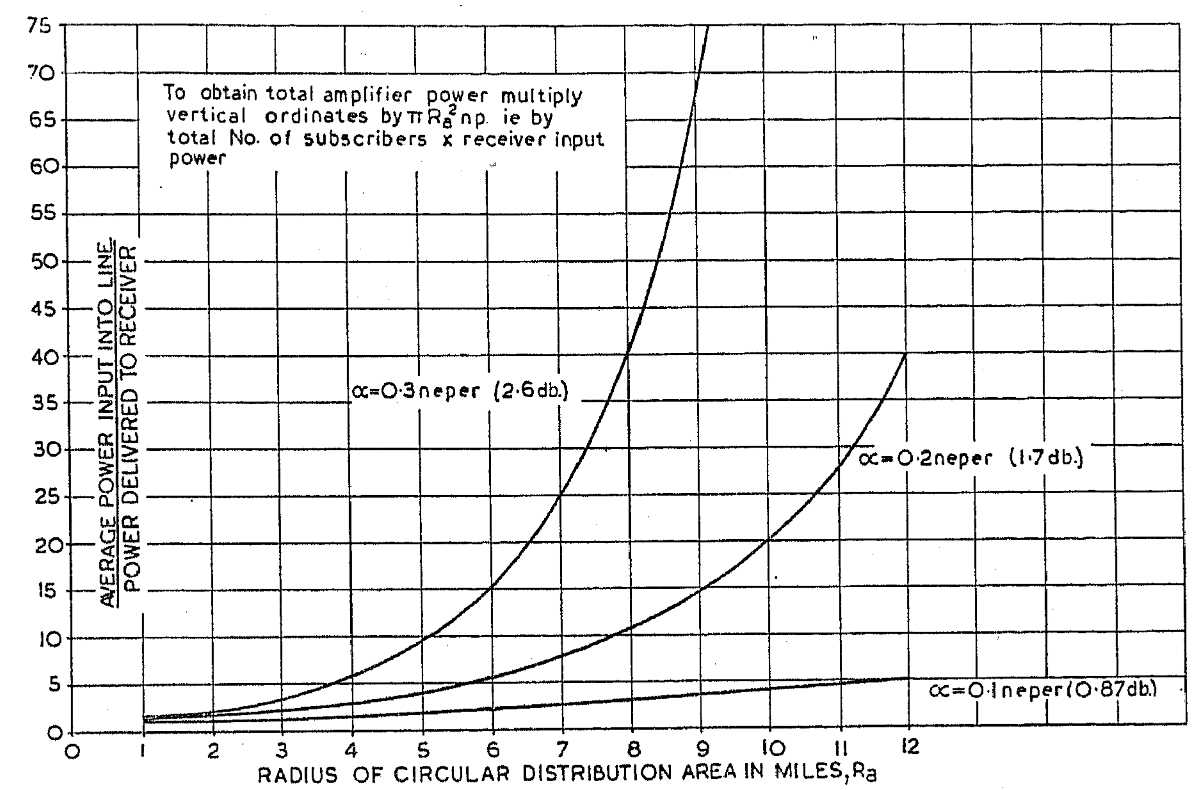

Fig. 16.—Average carrier power required for wire broadcast service on overhead lines.

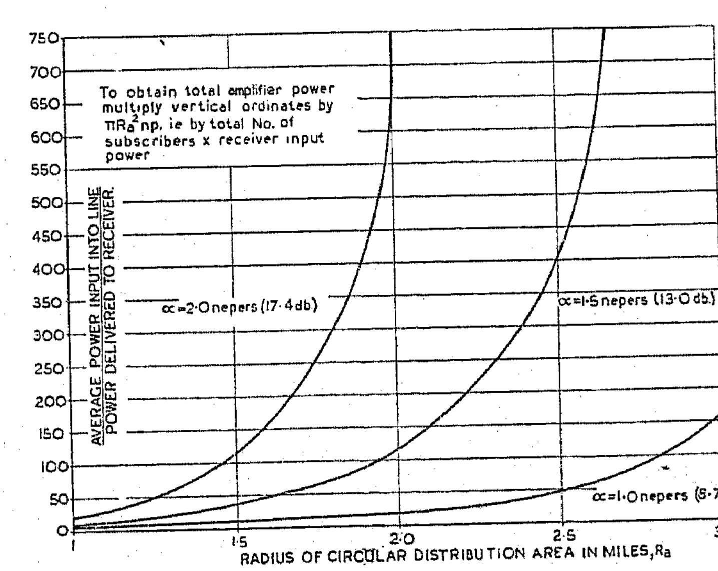

Fig. 17.—Average power required for wire broadcast service on underground lines.

Table 2

Type of line	Line attenuation per mile	Density of subscribers per square mile	Radius (miles) of local distribution area	Total number of subscribers	Total carrier power (watts) required to provide each receiver with 1 μW in case of underground feeders and 25 μW in case of overhead feeders	
					$\alpha = 1\cdot0$ neper	$\alpha = 1\cdot5$ nepers
Underground	1 neper (8·7 db.) and 1·5 nepers (13·0 db.)	500	1	1 570	0·0066	0·016
			2	6 280	0·13	0·7
			3	14 130	1·58	21·6
			4	25 120	16·3	614·0
		2 000	1	6 280	0·03	0·064
			2	25 120	0·51	2·8
			3	56 520	6·32	86·4
			4	100 480	65·3	2 456·0
Overhead	0·1 neper (0·87 db.)	100	1	315	0·0095	
			4	1 260	0·054	
			10	7 850	0·79	
		500	1	1 570	0·047	
			4	6 300	0·27	
			10	34 250	3·43	

example, from Fig. 18 it will be seen that if each local amplifying area were 7·5 square miles, which is equivalent to a circular area having a radius of about $1\frac{1}{2}$ miles, the total carrier power required to feed 1 million subscribers within a 50-mile radius would be 10 watts or 35 watts, according to whether the line attenuation per mile was 1·0 or 1·5 nepers. The attenuation of subscribers' lines lies between these limits. Thus in the case cited the power requirements compare very favourably with the power required for purely radio transmission.

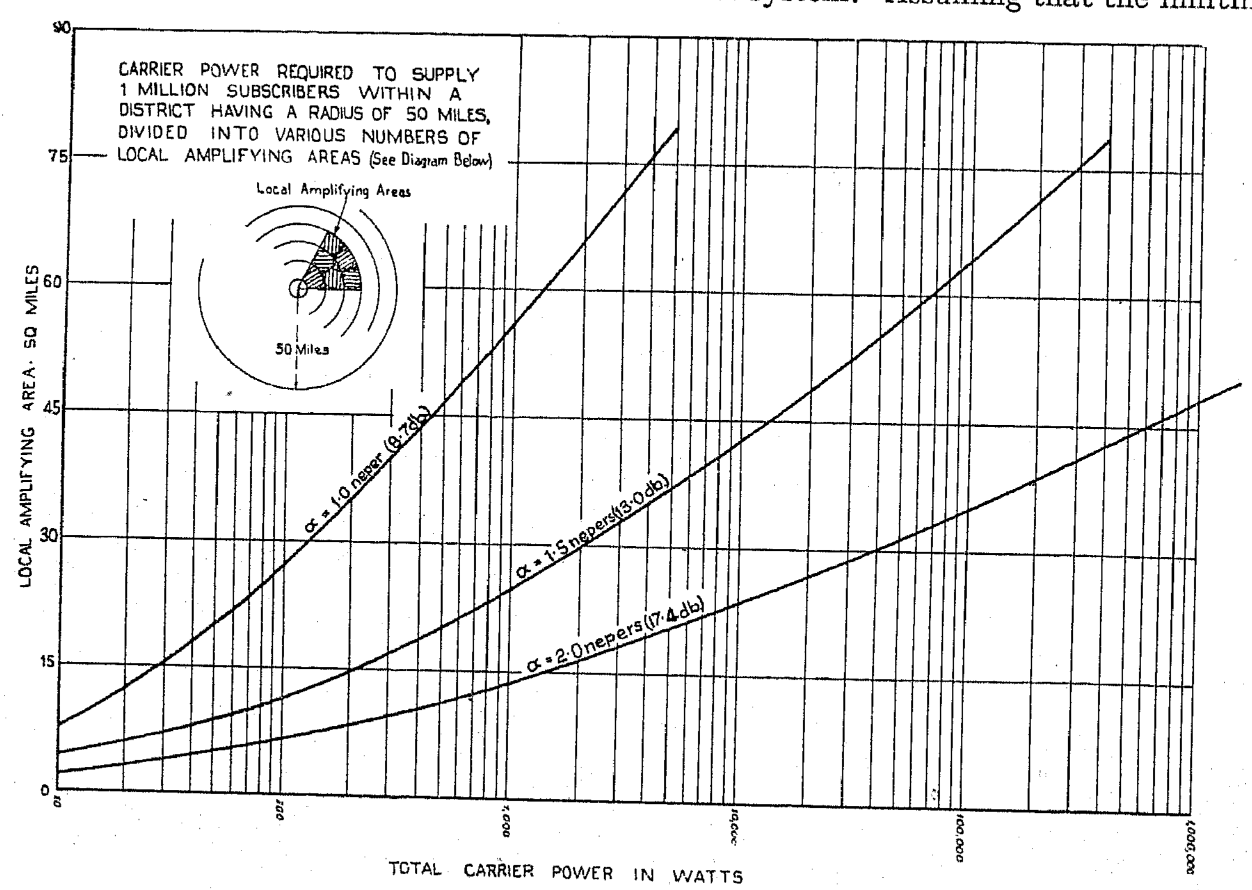

Fig. 18

Systems of Transmission

The ideal system of transmission from the point of view of economy of power is the single-sideband suppressed-carrier system. Assuming that the limiting factor in the valves of a power amplifier is the maximum permissible anode voltage, the total voltage in the case of a carrier double-sideband system is $qv(1 + m)$, where q is the number of carrier channels, V the peak voltage of each unmodulated carrier, and m the modulation coefficient, and this also represents the peak voltage permissible in a

single-sideband system. The ratio of the high-frequency outputs under the two systems is therefore

$$\frac{q^2v^2\left(1+\frac{m^2}{2}\right)}{q^2v^2(1+m)^2} = \frac{2+m^2}{2(1+m)^2}$$

where the denominator refers to the single-sideband systems whilst the ratio of the useful modulation outputs is $\frac{m^2}{2(1+m)^2}$. Thus for the same maximum valve voltage the approximate ratios of useful sideband energy, available at the valve output with the carrier plus double-sideband system modulated 80 %, 70 %, and 60 %, and with the single-sideband system, are — 10 db., — 11·0 db. and —11·5 db. respectively.

Although from the point of view of economy of energy the single-sideband suppressed-carrier system has obvious advantages, its adoption would require a special receiver, resulting in greater expense and complications. Moreover, to some listeners the fact that the average broadcast receiver can be used for both radio and carrier reception constitutes a definite advantage. The use of existing receivers limits the choice of carrier frequencies to the broadcast bands, although in many cases frequencies lower than those in the long-wave band would have advantages in that they have less line attenuation and they enable interfering station pick-up to be avoided to a greater extent. In choosing suitable frequencies in the broadcast band for a certain experimental equipment, considerable difficulty was experienced owing to the conflicting nature of the various requirements. For example, the frequencies chosen were to be such that a minimum of interference from powerful radio stations would be experienced; the frequencies had to be kept sufficiently far apart if complications in filter design were to be avoided, and yet close enough together if the available broadcast band was to be used for multi-carrier reception. Again, frequencies which result in third-order products falling within one or more of the selected carrier bands must be avoided to reduce intermodulation difficulties.[4] Thus even separation of frequencies within the band is undesirable. A final selection of frequencies made for the experimental scheme was 172, 216, 252·5, and 280 kc./s. Although in general these frequencies will be suitable in Great Britain, some modification might be necessary in certain cases, according to local conditions.

Layout of Carrier System utilizing Telephone Network

The planning of a carrier system of distribution over telephone pairs is dependent upon the layout of the telephone network. Provided line attenuation is not too great, the greater the local distributing area the better since large-output amplifiers can be used instead of a greater number of smaller-powered units distributed over the area. In consequence not only are capital and maintenance charges reduced but also the fault liability is lessened. It is not possible to formulate rigid rules regarding the best size of the local distribution area, but in general a radial distance of 2 miles from the final amplifier station seems a limiting economic figure. The total attenuation on subscribers' lines is such that an extension beyond this distance incurs an increase in size and cost of amplifiers that cancels the advantages.

A typical layout is shown in Fig. 19. Home and overseas programmes are conveyed at audio frequency from the broadcasting studios and the radio receiving station respectively to the main transmitting station, extensions being provided to sub-transmitting stations via audio-frequency amplifiers where necessary. At the transmitting and subtransmitting stations modulation and amplification of the carrier currents is effected, each station acting as a local distributing station and as a feeding station to the various local amplifying and distributing stations. The junctions might be energized direct from the local distributing amplifier or might have separate line amplifiers. The advantage of using the carrier instead of the audio system to provide the programmes to the

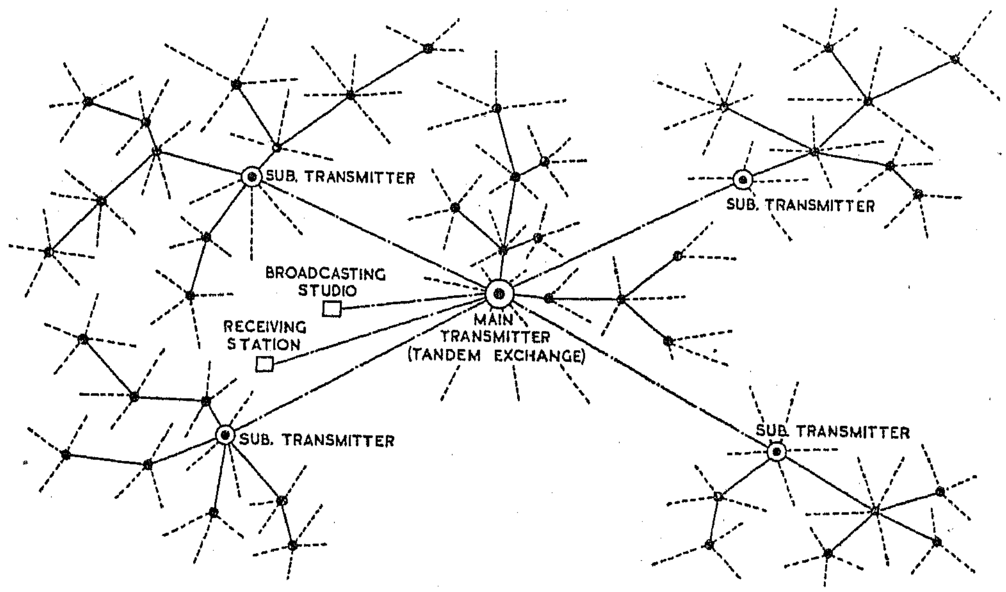

Fig. 19.—Typical layout of carrier distribution system of wire broadcasting.

● Exchange with amplifier.
——— H.F. feeder.
·—·— A.F. feeder.
------- Local telephone network.

various local distributing centres is twofold; a saving in junction feeders is effected, and a great reduction in the number of modulator and oscillator units is made.

A schematic diagram showing a method of introducing the carrier into the telephone lines and feeding the subscriber's amplifier is given in Fig. 20. Further reference is made to this later.

Transmitting and Amplifier Equipment

The requirements of transmitting and amplifying equipment for good-quality reproduction are fairly stringent. Frequency stability must be sufficient to avoid possible interference from strong broadcasting stations, since a small change in frequency might result in objectionable beat notes between radio and wire system carriers. When the carrier amplifier is delivering full power the set noise must be low, being at least 50 db. below the modulation signal, and the harmonic content of the output should be less than 5 % at any modulation frequency within the audio range. The intermodulation products should be at least 50 db. below the strength of the modulation output.

With regard to the fidelity, it is desirable that the amplification over each carrier band of frequencies should not vary more than $\pm$ 2 db. from the amplification at the mid-frequency of that band, whilst the gain stability should be such that the variation in gain due to all normal causes should not exceed 1 db.

When several amplifiers are used in series, as shown in Fig. 19, the requirements of individual units become more stringent. Intermodulation products, for example, when four amplifiers are in series, should be attenuated at least 60 db. in each amplifier.

The amplifiers and the carrier amplifying stages of transmitters might be either single-channel or wide-band, capable of dealing with the whole of the carriers. In any extensive system, both types of amplifiers have their uses. Where power output requirements are small, a wide-band amplifier is the more economic proposition. Failure of one valve, however, results in the loss of all programmes. If the output of a valve is decided by the permissible anode-voltage amplitude, the total maximum modulated output voltage per channel in the case of a valve used for multi-carrier amplification is $1/q$ the maximum modulated output for single-channel working, where q is the number of channels. This assumes that the degree of modulation is the same for all channels and that the peak modulation on all q channels occurs simultaneously. The ratio of output of modulation power of individual channels with multi-channel and single-channel amplifiers is $1/q^2$. Thus, if there were four programmes, a particular valve would be capable of giving a programme gain of 12 db. if single-channel working were adopted in preference to multi-channel working. As an offset to this gain in permissible output is the fact that a greater number of valves are required for single-channel working. In order to utilize some of the advantages of both types, an amplifier in which the low-level stages utilize the wide-band principle and the final power stages comprise single-channel amplifiers would be useful.

A particular transmitter equipment built for test purposes is shown in schematic diagram form in Fig. 21. A circuit diagram of the modulating and amplifying equipment is given in Fig. 22. The transmitter comprised four crystal-controlled oscillators, the output of each oscillator being applied across a tuned circuit be-

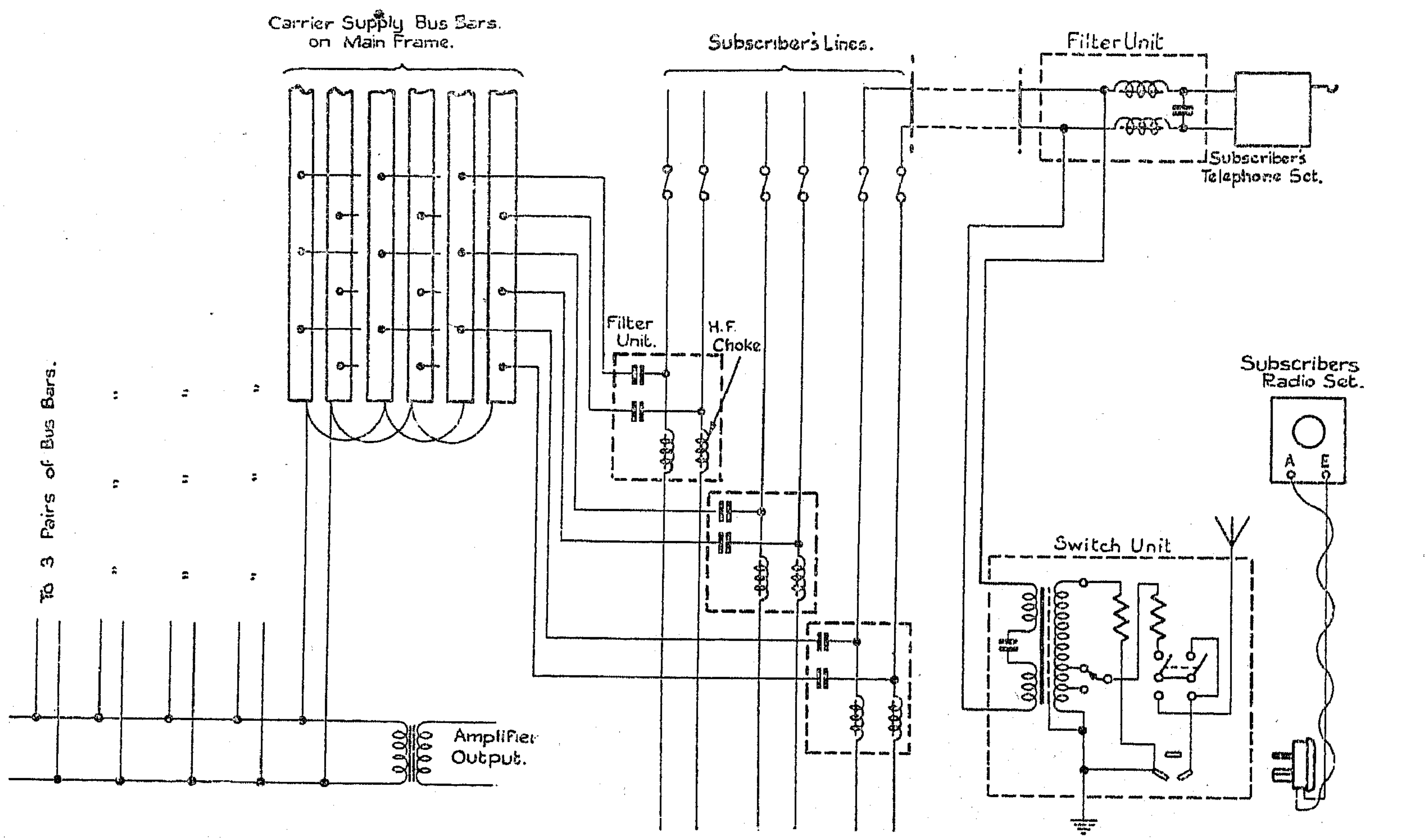

Fig. 20.—Carrier supply to subscribers.

tween grid and cathode of the modulated amplifying valve C. The anode circuit of the amplifying valve consisted of a high-impedance, low-Q-tuned circuit, this being obtained by using a high inductance and damping

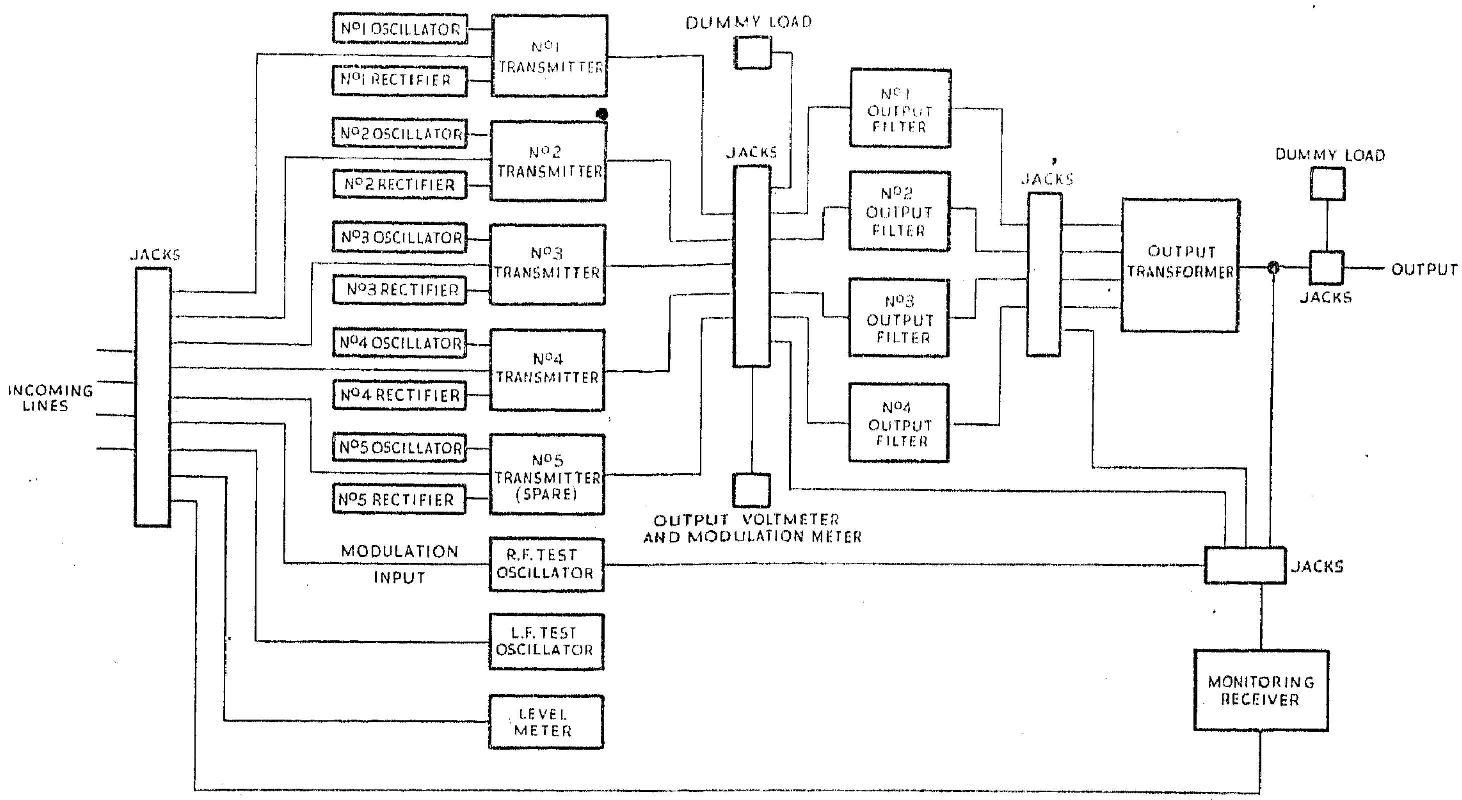

Fig. 21.—Transmitting equipment schematic.

down with a resistance of about 50 000 ohms, thereby producing a level response over the high-frequency sidebands. The resultant impedance in the output circuit

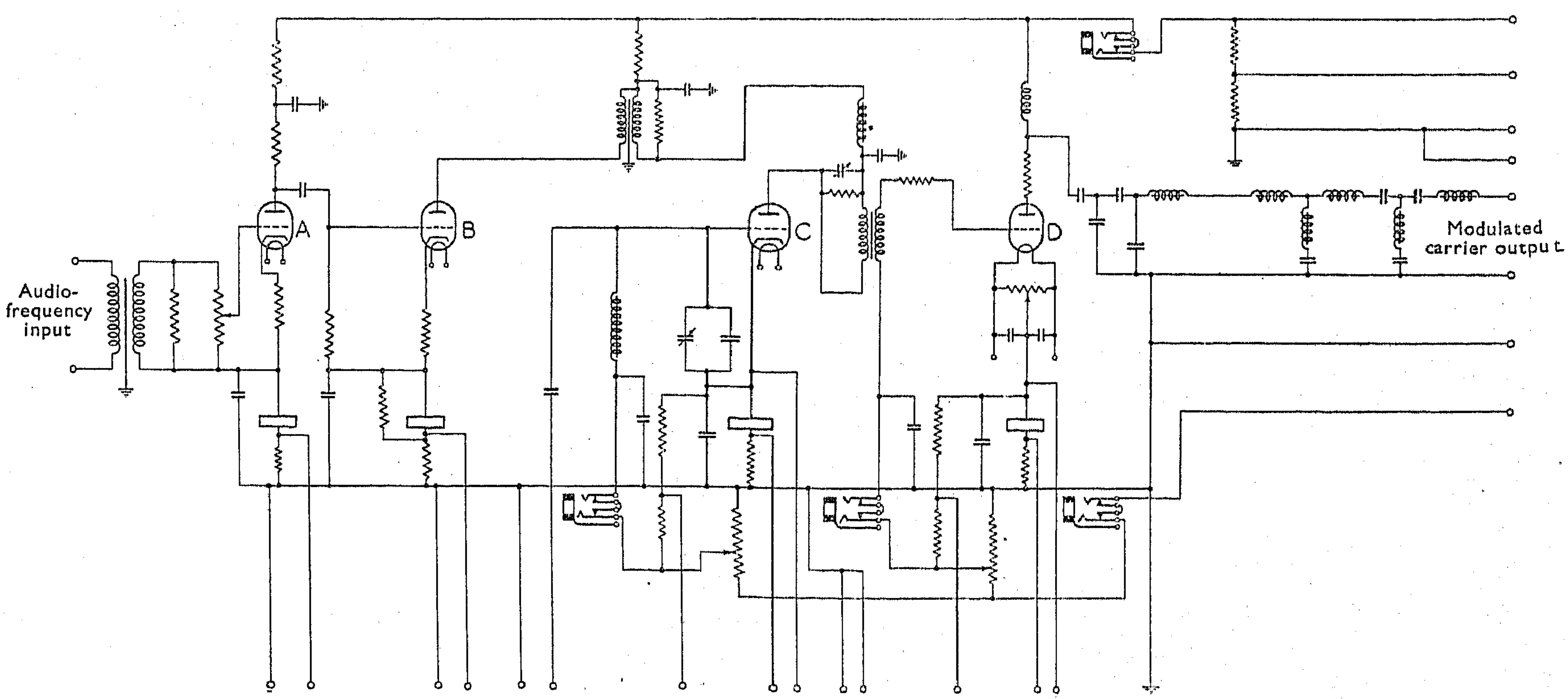

Fig. 22.—Four-channel carrier equipment. Transmitter circuit diagram.

of valve C was still high compared with the valve impedance. Valve C was coupled to the output valve D, which was arranged in Class B as a linear amplifier. To match this valve to the required output impedance an impedance-changing band-pass half section was used, combining the function of an output transformer and the necessary band-pass filter. Subsequently the output stage was altered to use Class A amplification, the advantage being a less critical adjustment of the stage.

Each programme was supplied through a step-up transformer to a valve A which was resistance-coupled to the modulator B. Anode modulation was employed with transformer coupling. Both valves had a small amount of negative feed-back obtained by omitting the normal decoupling condenser across the bias resistance.

Typical performance curves of the transmitter are given in Figs. 23, 24 and 25. The characteristics could have

been improved but were considered good enough for the purpose of providing carrier to existing radio broadcasting receivers.

With 60 per cent modulation the carrier power at the output of the transformer was about 2·4 watts per channel, and intermodulation levels were of the order of — 60 db. At 1 000 c./s. with audio-frequency input levels of — 10 db. with reference to 1 milliwatt in 600 ohms, the signal/noise ratio was approximately 50 db. Carrier harmonics were at least 70 db. below the fundamental.

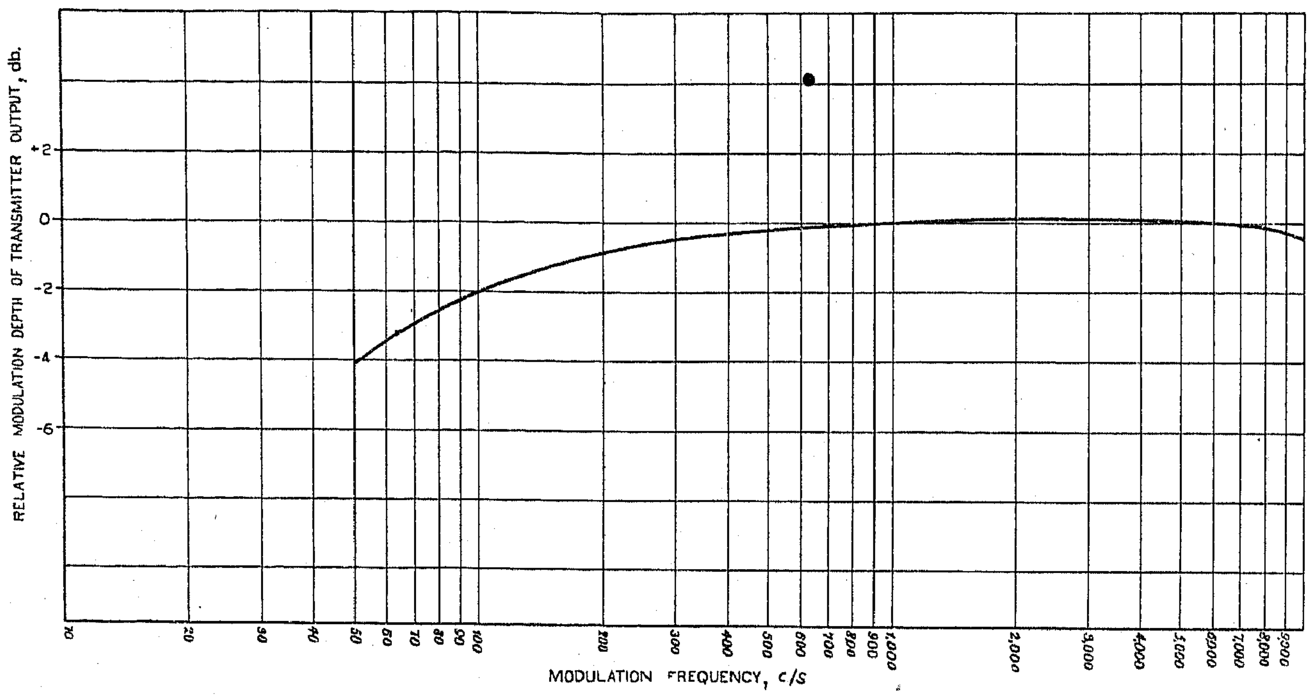

Fig. 23.—Transmitter frequency/modulation characteristic. Constant low-frequency input.

Exchange Carrier Feeding and Filter Equipment

The problem of feeding the carrier energy into telephone pairs is both technical and economic. On the one hand it is necessary to reduce to a small amplitude interfering currents in the lines emanating from the telephone exchange equipment and preventing carrier currents from circulating at appreciable amplitude in telephone-circuits other than the lines; on the other hand it is essential that the costs should be kept reasonably low. Furthermore, it must not be forgotten that the primary purpose of a telephone system is to provide an efficient telephone service and that the broadcast service is of secondary importance. Thus any filters introduced in the telephone circuit must not appreciably interfere with the efficient working of the service, either by increasing maintenance difficulties or by degrading the quality of transmission. The filter and feeding units must therefore be readily accessible and must present a low impedance to audio-frequency currents passing along normal telephone circuits. The fact that the modern tendency is to extend the audio band of frequencies for commercial telephony must be borne in mind in filter design. The manner in which these various requirements can be met is indicated below.

Perhaps the most desirable manner of introducing the carrier into the various telephone pairs at the exchange is to use an auxiliary frame on which all pairs intended for carrier working are terminated as required, extensions to the main frame being provided. Apart from the fact that this method enables the carrier feeding equipment to be designed free from the imposition of the space limitations experienced when the equipment is fixed on the main frame, it provides a method whereby correct groupings of feeders can be made. The desirability of feeding pairs in groups arises from the fact that those subscribers who are located near to the amplifiers require much less power input at the exchange end of the line than subscribers located near the outside boundary of the exchange area. Normally, however, no special effort is made at exchanges to group telephone subscribers according to the length of their lines from the exchange. Against the advantages enumerated is the fact that the use of auxiliary frames might cause congestion of the extensions (jumpers) to the main frame. Furthermore, the space required for the equipment is not available in many exchanges. It thus becomes necessary to provide

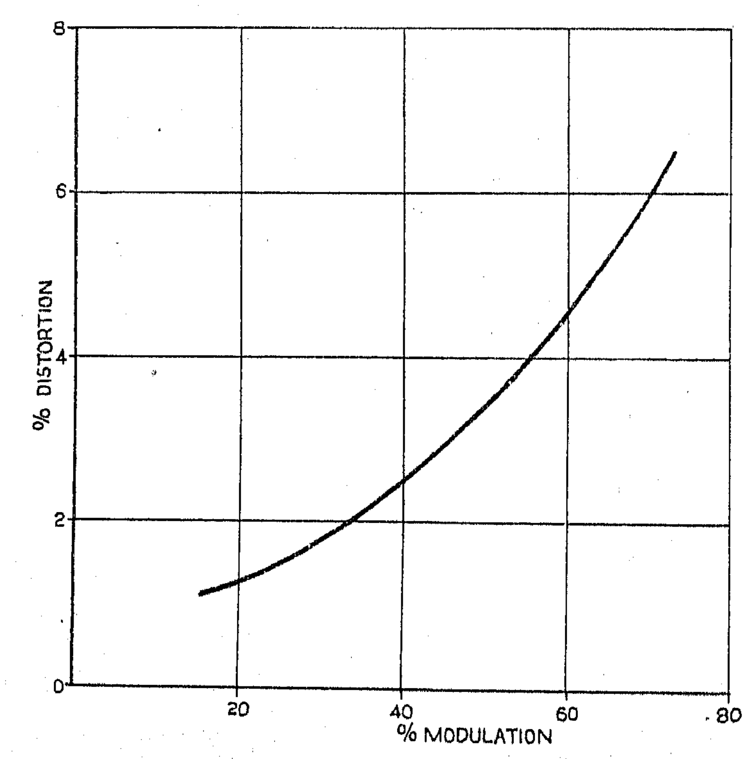

Fig. 24.—Transmitter modulation/distortion characteristic. Modulation frequency 1 000 c./s.

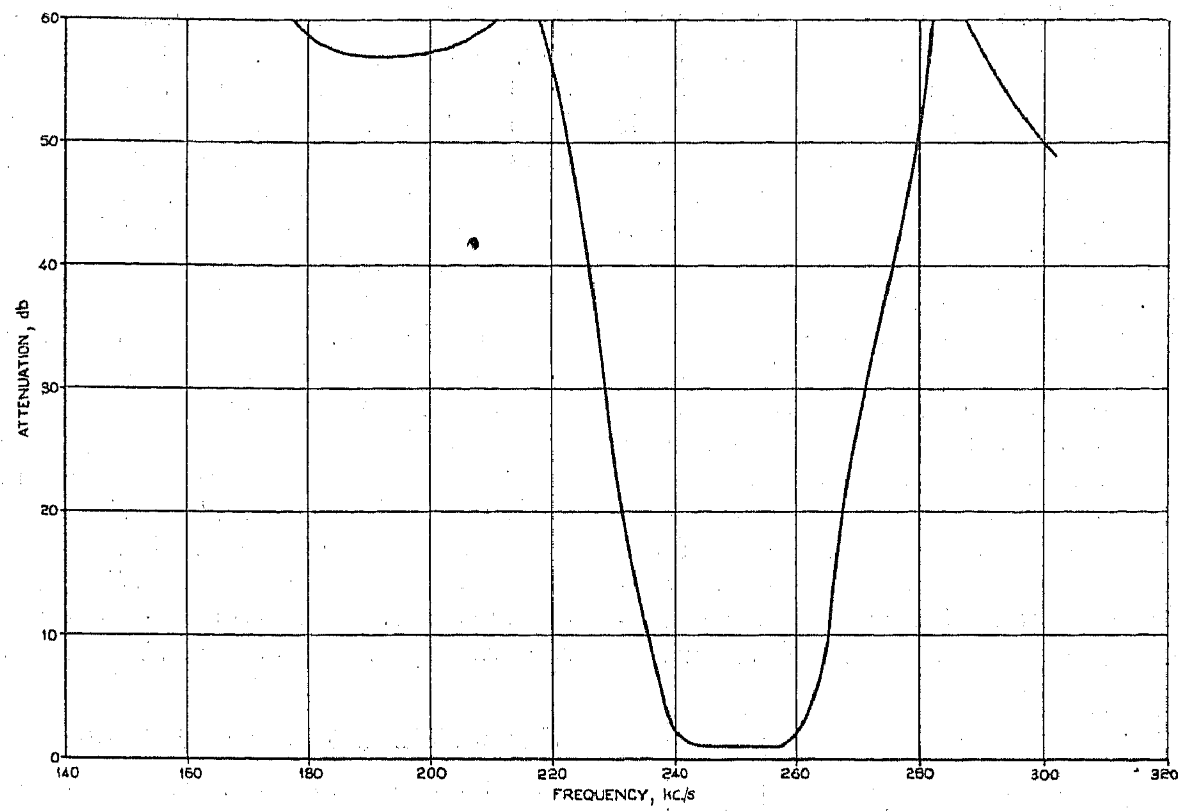

Fig. 25.—Frequency/attenuation characteristic of transmitter band-pass filter.

filters and feeding equipment that can be fitted to the main frame, and so to design the circuits that the individual carrier requirements of each line can be met within reasonable limits. The manner in which that was accomplished in the case of an experimental equipment is shown in Figs. 20 and 26. Behind the protector fanning strip, two vertical brass busbars $\frac{3}{8}$ in. wide by $\frac{1}{4}$ in. thick, spaced $\frac{9}{16}$ in. between centres, are fixed. Connected to these busbars are the carrier filter and

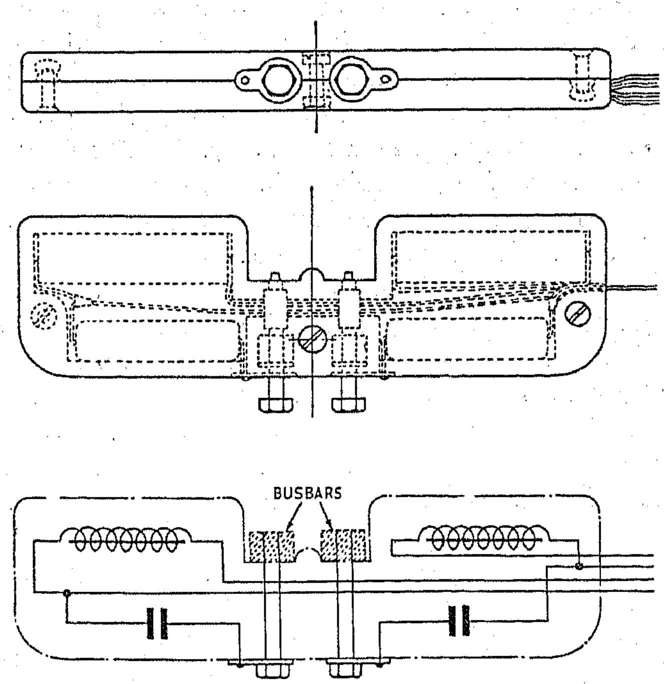

Fig. 26.—Exchange filter unit.

feeding units, one for each telephone pair. The dimensions of the moulded cases containing the condensers and high-frequency chokes which constitute the feeding and filter unit are $4\frac{9}{16}$ in. $\times$ $1\frac{1}{4}$ in. $\times$ $\frac{15}{64}$ in. The output terminals of the carrier transmitter or amplifier are connected to the busbars via transformers, and diversions of any lines requiring a carrier supply are made via the filter unit to the protectors, the necessary connections being facilitated by the use of an auxiliary vertical tag strip. The high-frequency chokes are wound on and encased in rhometal strip, as this construction was found to give all the suppression and reduction in audio-frequency cross-talk desired at a minimum cost. Tests made to ascertain the effectiveness of the chokes in reducing parasitic currents in the carrier band showed that the attenuation varied from 25 to 30 db. round about frequencies of 200 kc./s. The effect upon the audio-frequency currents is shown in the curve of Fig. 27. To obtain this curve, a mixed telephone circuit extending from a tele-

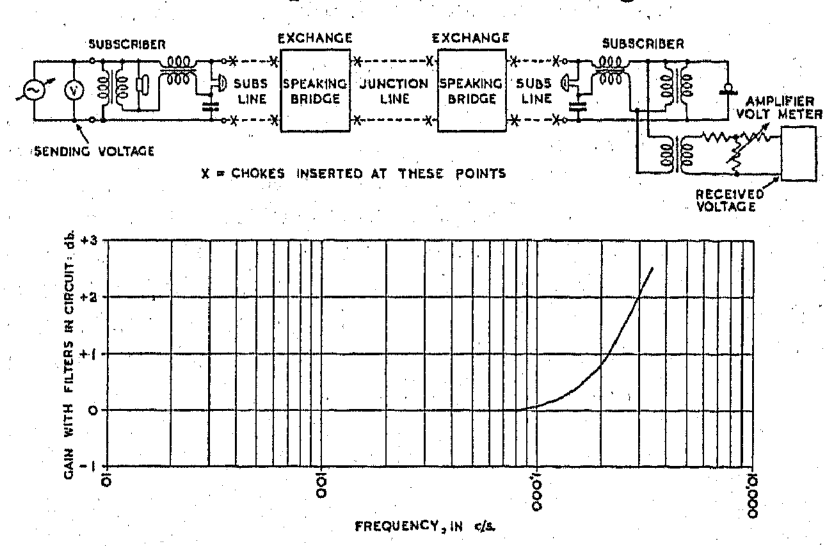

Fig. 27.—Effect of carrier filters on speaking efficiency of telephone circuit.

phone subscriber's premises, over an underground pair to a satellite exchange, via a junction circuit to a parent exchange, and thence to another telephone subscriber, was made. There were thus 12 high-frequency chokes in series over the whole circuit. The various sections of the circuit consisted of telephone pairs having the attenuation

characteristics shown in Fig. 28. A constant voltage at various frequencies was maintained at one end, and the voltage level of the remote end was measured. It will be seen that actually at certain frequencies the circuit characteristics were improved, owing no doubt to the partial neutralization of the capacitive reactance by the chokes. A theoretically ideal system of feeding subscribers' lines would be to group on the same busbars all those pairs requiring approximately the same voltage input, and provide suitable voltages to the various busbars by means of transformers, As previously explained, in practice such a grouping is not usually convenient and in many cases the lines of a near and distant subscriber are close together on the main frame. It is thus better to maintain the same voltage across all busbars and to adjust the carrier input into each line by means of the carrier feeding condensers. In the test installation previously mentioned, three sizes of condenser were standardized: $0 \cdot 01\ \mu F$ for subscribers on the outer fringe

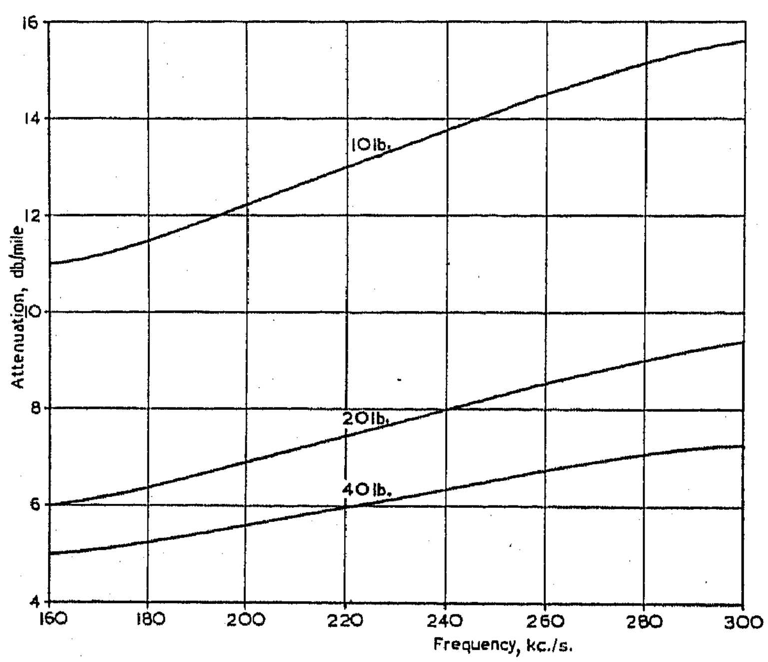

Fig. 28.—Attenuation of telephone pairs.

of a telephone area of about 2 to 3 miles' radius, $0 \cdot 003\ \mu F$ for subscribers between 1 and 2 miles' radius, and $0 \cdot 001\ \mu F$ for close-in subscribers. To facilitate step-down requirements the carrier output transformers originally had five similar secondary windings each in series with an inductance adjusted to neutralize the capacitive reactance of the feeding circuits, but in a later design it was found possible to dispense with the series arrangement and to feed 15 sets of busbars in 5 groups of 3, as shown in Fig. 20.

Subscriber's Service Feeders

With a complete underground system of distribution the interference currents introduced into the carrier lines, due to pick-up of other fields caused by radio signals or radiation from industrial plant, is very small. When, however, any part of the circuit consists of open wires, the interference currents can be very appreciable. A typical case illustrates this fact. An underground pair was connected at a distribution point to an overhead pair 410 yards long, a part of which ran parallel to trolleybus wires supported on standards on the opposite side of the street. The portion parallel to the trolley wires—65 yards long—was replaced by a twin cable, with the result that the noise level in the subscriber's premises fell from − 72 db. to − 106 db., referred to 1 volt. Other tests have confirmed the fact that nearby sources of disturbance can be rendered less harmful by the use of cable in preference to open wires, the close spacing between the wires of the cable being responsible for the reduction in pick-up. Similar results were not observed when the interference was due to distant radio stations. In many cases of open-wire lines connected to underground pairs at the distribution position the replacement of the overhead open section by an overhead-cable pair did not effect appreciable reduction in the pick-up of radio interfering signal, a lack of balance in the cables or some other part of the circuit being responsible for the pick-up. In some cases a small reduction in the interference signals could be made by earthing the centre of the primary of the subscriber's screened transformer.

Subscriber's Filter and Feeding Arrangements

It is essential to insert carrier-frequency chokes in the subscriber's telephone connections to reduce the interference due to dialling currents and to prevent carrier currents from circulating in the subscriber's telephone circuits. In addition to chokes and feeding condensers, a terminating screened transformer is needed for the connection to the receiver. The need for screening arises from the fact that the receiver input circuit is unbalanced, one side being connected to earth. This unbalance, unless corrected, would cause in some cases a serious increase in interference voltages induced in the connecting pairs. Thus the best arrangement for the carrier feeding and filter equipment is to place the screened transformer in the same case as the change-over switch—when the receiver is intended both for radio and for line carrier reception—and to assemble the chokes and condensers together in a separate case (which can be fixed at a convenient place away from the receiver). To reduce pick-up to a minimum, the secondary leads, terminated in the unbalanced receiver load, should be as short as possible and should preferably be screened.

The extent to which even screened leads when imperfectly earthed can be affected by interference fields will be appreciated from the results of a particular test. A screened pair 7 yards long was used to connect the subscriber's transformer to his wireless set. With the receiver end of the screen earthed, the interference due to a certain long-wave broadcasting station was −72 db. with reference to 1 volt. When both ends were earthed the interference dropped to −106 db.

The transformer units should thus be located in or near the receiver. Generally the choke and condenser unit is preferably located near the telephone connector box, where connections to the telephone lines can readily be made. Fig. 29 gives a perspective view of the listener's combined transformer and switching unit. A flexible cord, which can be plugged into the switch unit, is provided for connection to the receiver.

The transformer windings are wound on iron-dust cores and give a transformer ratio of 1 : 1 under normal circumstances. In those cases where, owing to the high

noise-level in the line circuit, it is necessary to increase the carrier voltage-level to the primary of the transformer, a step-down transformer might be needed to prevent an excessive voltage on the grid of the first valve.

A question that requires some detailed consideration is the desirable value of terminating impedance at the end of the subscriber's pair. To extract the maximum energy and to avoid reflections it is usually considered necessary to have a terminating value equal to the characteristic impedance of the line. However, these considerations in the majority of cases do not apply to carrier working over telephone subscribers' pairs, since the voltage available at the subscriber's end of the line is usually higher than is strictly necessary and the attenuation of the line is sufficiently high to reduce the reflected wave at the exchange

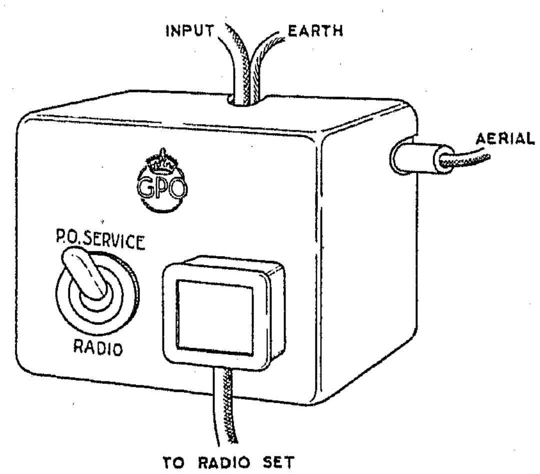

Fig. 29.—Carrier system. Listener's change-over switch.

to such a value as not to affect appreciably the sending-end impedance. This latter statement is supported by the results of the following analysis. The sending-end impedance Z_s of a line can, by a rearrangement of the usual expression, be shown thus:—

$$Z_s = Z_0\frac{(A+B)\cos\beta l + j(A-B)\sin\beta l}{(A-B)\cos\beta l + j(A+B)\sin\beta l} \quad . \quad (5)$$

where $A = Z_0(1+k)e^{\alpha l}$
$B = Z_0(k-1)e^{-\alpha l}$
$K = \dfrac{Z_L}{Z_0}$

By substituting the values of A and B and by rationalizing the denominator, expression (5) becomes

$$Z_s = Z_0\frac{(1+K)^2e^{2\alpha l} - (1-K)^2e^{-2\alpha l} + 2j(1-K^2)\sin 2\beta l}{\left\{(1+K)^2e^{2\alpha l} + (1-K)^2e^{-2\alpha l} + 2(1-K^2)\right\}\cos^2\beta l + \left\{(1+K)^2e^{2\alpha l} + (1-K)^2e^{-2\alpha l} - 2(1-K^2)\right\}\sin^2\beta l} \quad (6)$$

By differentiating expression (6) with respect to l and equating to zero, an expression is derived which enables the value of l to be obtained when Z_s has its greatest and lowest values.

In its final form the expression is

$$\alpha\left[ce^{-\alpha l} + D(\cos^2\beta l - \sin^2\beta l)\right] + \beta D\sin 2\beta l = 0 \quad (7)$$

where $C = (1-K)^2$
and $D = 1 - K^2$.

It follows that if the attenuation is small, that is if α is negligible,

$$\sin 2\beta l = 0$$

or
$$l = \frac{n\lambda}{4}$$

Thus when the attenuation is very small the sending-end impedance attains minimum and maximum values when the line is a multiple of a quarter-wavelength long. By substituting normal values for attenuation and phase constant in expression (7) it can be shown that this relationship is substantially correct for telephone cables.

With regard to the phase angle ϕ, from (6) the following relationship holds:—

$$\tan\phi = \frac{2(1-K^2)\sin 2\beta l}{(1+K)^2e^{2\alpha l} - (1-K)^2e^{-2\alpha l}}$$

Thus

$$\frac{a\tan\phi}{dl} = \frac{4\beta(1-K^2)\cos 2\beta l\left[(1+K)^2e^{2\alpha l} - (1-K)^2e^{-2\alpha l}\right] - 4(1-K^2)\sin 2\beta l\left[(1+K)^2e^{2\alpha l} + (1-K)^2e^{-2\alpha l}\right]}{\left[(1+K)^2e^{2\alpha l} - (1-K)^2e^{-2\alpha l}\right]^2}$$

By equating to zero and rearranging,

$$\tan 2\beta l = \frac{\beta\left[(1+K)^2e^{-2\alpha l} - (1-K)^2e^{-2\alpha l}\right]}{\alpha\left[(1+K)^2e^{-2\alpha l} + (1-K)^2e^{-2\alpha l}\right]}$$

which is the condition for maximum value of ϕ.

When the attenuation constant α is very small,

$$\tan 2\beta l = \infty$$

that is,
$$l = \frac{(2n\pm 1)\pi}{4\beta} = \frac{(2n\pm 1)\lambda}{8}$$

Thus the maximum phase angle occurs when l is an odd number of eighth-wavelengths.

When the attenuation is high the expression becomes $Z_s = Z_0$, even for small values of l. In other words, the sending-end impedance is not greatly affected by the receiving-end load. If, however, the attenuation is very low, the value of Z_s approximates to[5]

$$Z_0\frac{K + 0{\cdot}5j(1-K^2)\sin 2\beta l}{\cos^2\beta l + K^2\sin^2\beta l}$$

The values of Z_s denoted by this expression vary between KZ_0 and Z_0/K. Thus the sending-end impedance of lines having negligible attention can vary in the extreme ratio of K^2.

For ordinary telephone cables where β/α is considerably greater than unity the maximum value of ϕ measured at the sending end occurs when the length of line is not much different from an odd number of eighth-wavelengths long, even though the mismatch is considerable. For example, if $K = 0{\cdot}5$, the values of $\tan 2\beta l$ for maximum phase angle vary between β/α and $\beta/(1{\cdot}25\alpha)$ between the limiting values $2\alpha l = \infty$ and 0. For a certain underground cable, in which the value of $\beta = 10$ radians per mile and $\alpha = 1{\cdot}15$ nepers per mile, $\tan 2\beta l$ lies between $8{\cdot}7$ and $7{\cdot}0$ (approximately), giving a maximum phase angle when the length of line is

some value between $(\frac{1}{4}n \pm 0\cdot119)\lambda$ and $(\frac{1}{4}n \pm 0\cdot114)\lambda$ respectively.

Curves for the sending-end impedance of a typical underground telephone pair and an overhead open-wire pair are given in Fig. 30. In practice there may be appreciable departure from the values of the constants chosen, but the curves serve to illustrate the fact that as a broad generalization, from the aspect of connecting long pairs to common busbars for carrier working and ensuring an equable distribution of energy amongst the pairs, correct terminal matching is not so important in the case of cable pairs as in the case of overhead low-attenuation pairs. However, even with underground cables when the lengths are short, terminating impedances equal approximately to the cable characteristic-impedance are desirable owing to the large difference that would otherwise be experienced in the modulus and phase angle of pairs differing in length by small amounts only.

In the test installation previously mentioned, a terminating impedance of about 300 ohms was normally found satisfactory for the longer underground pairs, even when these were continued from the distribution position in open-wire lines.

Where several extensions are made from the telephone subscriber's pair for the purpose of providing a carrier broadcast service to nearby non-telephone subscribers, a more correct termination at the listener's end of the line is necessary.

Even though the spurs are terminated in the characteristic impedance of each spur, the combination of several spurs connected across the main feeder at different points gives rise to complications and imposes a limit to the number of branch lines so connected. Unless care is taken with line terminations, according to the lengths of the spurs and the points at which they are connected to the main feeder, a wide difference in the voltages available at the listener's ends of the spurs will be experienced.

Thanks are given to the Engineer-in-Chief to the Post Office, Colonel A. S. Angwin, D.S.O., for permission to present this paper. Appreciation is also expressed to him and to the former Engineer-in-Chief, Sir George Lee, for sustained interest and support. It is impossible adequately to register the author's gratitude to all those members of his staff who by their enthusiasm and hard work have elucidated many difficult problems relating to the practical application of carrier current to wire networks. In particular, thanks are due to Messrs. I. J. Cohen, P. L. Barker, W. G. N. Chew, T. W. Baker, and their assistants, for their good work.

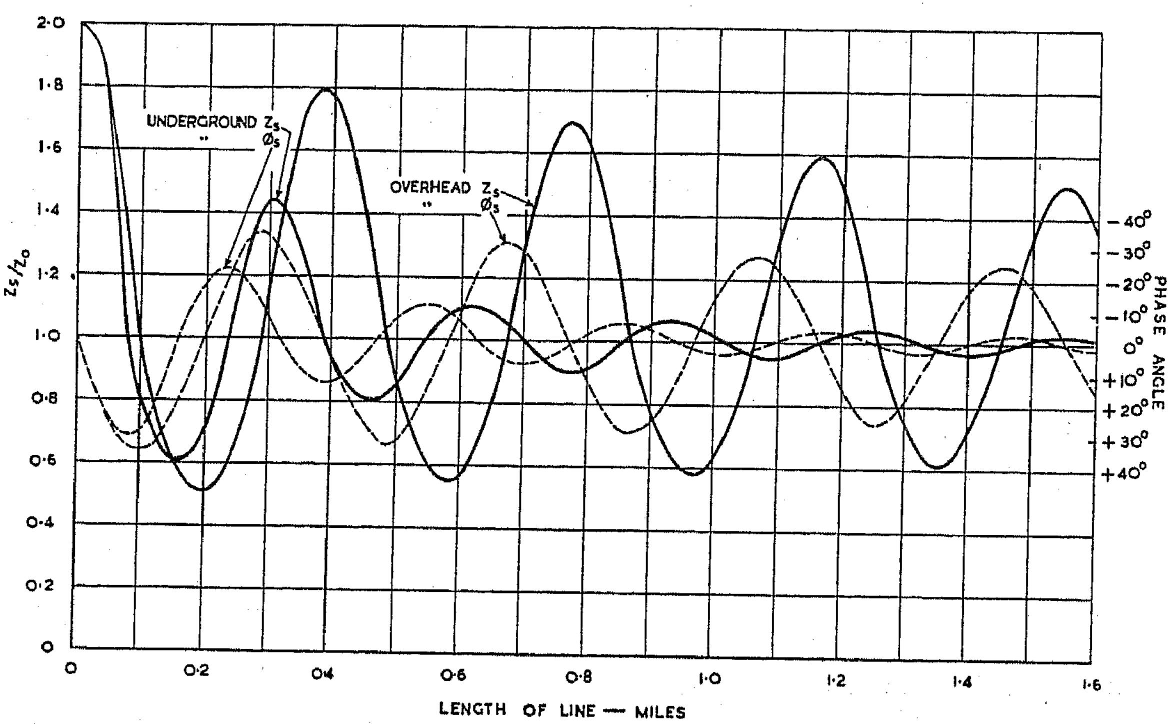

Fig. 30.—Approximate variation of sending-end impedance with length of lines terminated in resistance equal to twice the characteristic impedance (calculated).
Underground cable, $\alpha = 10$ db. (8·7 nepers); $\beta = 10$ radians/mile.
Overhead pair, $\alpha = 1$ db. (0·87 neper); $\beta = 7\cdot9$ radians/mile.

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[The discussion on this paper will be found on page 101.]

DISCUSSION BEFORE THE WIRELESS SECTION, 6TH MARCH, 1940

Mr. P. P. Eckersley: The author's statement that only about 3 % of the total number of British listeners receive their programmes by wire may be misleading. Had the position of the rediffusion companies been more clearly defined throughout the development of wire broadcasting that figure would have been considerably increased, perhaps to the figure of 50 % which has been reached in Holland.

Broadly speaking, the paper is a statement of the various methods by which a wire broadcasting system can be consummated. There is no question that the audio system, with a buried network, is the best technical method; it gives better quality and greater reliability than the other methods but it is impracticable as it means digging up the streets to lay the network. The overhead audio system may introduce frequency-characteristic distortions, and I suggest that the author should include in his list of References a paper dealing with this question which I read before the Wireless Section in 1934.* The combination of the inductance of the open-wire leads and the capacitance of the down leads causes some rather violent distortions unless precautions are taken to terminate the feeders with resistance.

The carrier systems which make use of the supply mains have as their chief advantage over those which rely on telephone wires the fact that the mains go into 5 times as many houses as the telephone. Nevertheless, from a purely technical point of view, it is easier to use the telephone than the mains network. But if both are practicable and both economic and one has a wider application, it should be used wherever possible.

In costing the telephone system the expense of writing off the associated wireless receiver presumably has to be added to the weekly charge for the service. I should like the author to tell us how much the charge would be with the extended wiring system. To this must be added the charge for the telephone. If the telephone were installed in order to make the wire broadcasting service available then some charge should be added.

In the scheme we devised, using the mains network, we found it better to employ much lower frequencies than those used by the author in his experiments. We furthermore devised a method of distribution in which the load variations did not vary the signal level. We found that, using special methods of distribution and lower frequencies, the necessary power per consumer was 2 mW, not 16 mW as found in the author's experiments. We provided a " selector " which when plugged into the mains gave four or six alternative programmes; we never planned to use an ordinary wireless receiver with its greater complication and often mediocre performance.

Turning to the problem of the bridging of transformers, it was found in some experiments which were made in America, where high-frequency currents were passed through the transformers and where the domestic load was energized by the high-frequency currents, that when any device the high-frequency impedance of which varied in sympathy with the power currents was connected across the mains, the superimposed currents were modulated in intensity at the frequency of the power currents. In other words, " hum modulations " were created.

We do not require either to strap transformers or to pass high-frequency currents through them, because in British practice there are far more consumers connected to the secondary of a single transformer than in American mains layout. This fact makes it economic with British networks to energize each secondary network from separate repeaters. A conductor carrying the output of all the transmitters interconnects the substations and energizes the repeaters.

The author rightly says that one of the chief difficulties of the mains system is the extremely low surge impedance of the network. There is furthermore the point that unterminated feeders can have an actual impedance lower than their surge impedance. In certain substations, 10 feeders may be brought together, giving actual impedances of the order 0·1 or 0·2 ohm. The difficulty of designing feeders and transformers to feed high-frequency currents into such networks is considerable; we have overcome our problems more by careful design than by any special devices.

We believe that our mains system is ubiquitous, economical and practicable, but I fully agree that the telephone network system has many advantages. It would appear the wisest to combine all and any systems so that each is used according to its suitability for a given set of conditions.

Mr. W. West: I am impressed by the potentiality of the audio-frequency system for supplying a uniformly high-quality service. The controls which the subscriber has to operate are such that at no possible setting can the distortions exceed the small tolerances to which the system as a whole has been designed. The volume control, for example, is limited to a variation of ± 10 db. from the level which is selected as normal; this avoids the fault (not uncommon among listeners to radio programmes) of turning up the volume to such a stentorian level that not only are most of the sounds too unnaturally loud but also severe distortion is being introduced by the amplifier. The limitation of the volume level is in my opinion a definite asset, and it has the incidental advantage of reducing the possibility of the noise nuisance to neighbours. The comparative immunity of the audio-frequency system from noise interference has been mentioned by the author; another valuable feature, from the point of view of programme quality, is that the power amplifier is continuously under skilled maintenance. With other systems for receiving broadcast programmes the amplifier is at the listener's premises and subject to maintenance at his own discretion. The gradual deterioration of the valves over a period of months, or years, causes an insidious degradation of quality to which no attention may be given before the condition has become chronic. If, in addition, the service were supplied by an organization which is able to obtain all its equipment on the basis of acceptance tests to a high-grade performance specification, listeners would have access to a higher standard of quality of reception of broadcast programmes than is now available, and at a cost which

* *Journal I.E.E.*, 1934, **75**, p. 333.

the author has calculated to be comparable with that which is ordinarily paid.

I am interested in the manner in which the levels available on the subscriber's volume control were selected, and perhaps the author can give some further information. At the normal (i.e. the middle) setting, is the loudness of the announcer's voice approximately the same as would be used by a person in the room when speaking in general conversation to people in the room who are not otherwise engaged in conversation?

In connection with the design of the loud-speaker, the author mentions that an axial sound-pressure characteristic rising at a rate of 2·5 db. per octave is required. To avoid possible misunderstanding, I take this opportunity to mention that this rule is not suggested for universal application to loud-speaker design. It is derived from the finding that, for the average listening position in a living room, the reverberant sound predominates over the direct sound. From this it was deduced that a uniform frequency-characteristic of total sound power radiated is required from the loud-speaker, and it was found that, with the particular type of loud-speaker which the author has described, uniform total power corresponds very closely with a rising characteristic for axial sound-pressure at 2·5 db. per octave. The axial sound-pressure is the more convenient practical criterion of performance, since the measurement is more simple and direct.

Dr. R. L. Smith-Rose: In view of Mr. Eckersley's remarks in favour of the dissemination of music and speech by wire, it is interesting to ask why he did not introduce wire broadcasting following his early experiments at Writtle, and so forestall the introduction of wireless broadcasting. If Mr. Eckersley had been born a little earlier and had been chief engineer of the Electrophone Company in 1895, the B.B.C. might possibly never have existed. The fact is, of course, that although those early experiments did show the possibility of distributing programmes over wires, they were a little before their time, and it was not until after the introduction of wireless broadcasting that there were developed the technical apparatus and equipment which have made the re-establishment of wire broadcasting at all feasible.

I should like the author to explain how the difficulty of interference has been overcome in the use of apparatus connected either to the power mains or to the telephone line. My experience is that telephone lines are not as free from interference as is a good broadcasting receiver at the present time. One of the most serious sources of disturbance in a radio receiver is the interference which is conveyed along the electric supply mains, and fed into the receiver either by conduction or by radiation from neighbouring mains. It would seem that when the whole of the programme was taken from the mains there would have been still greater difficulty, and I should be interested to know how this has been overcome.

The use of a radio receiver in conjunction with wire broadcasting surely introduces an additional source of interference, namely direct reception of broadcasting on the receiver itself, and I should like to ask how this has been eliminated. In the author's demonstration receiver the screening seems to have received considerably more attention than is customary with ordinary commercial receivers.

Mr. F. L. Coombs: I agree with Mr. Eckersley that the author's statement that only 3 % of the total number of British listeners receive their programmes by wire is rather misleading. In areas where wire broadcasting is available, the proportion of licence-holders receiving this type of broadcast is nearer $33\frac{1}{3}$ %, and in one town of 8 000 houses where a wire broadcasting system operates there are more than 4 000 subscribers.

I should like to know whether the author has carried out any research into the broadcasting of high-frequency signals over the networks of audio systems which are now in existence. These networks are not subject to the same difficulties as the mains from the point of view of transformers at the distribution substations, and they have a considerably higher characteristic impedance. If it were found possible to transmit high-frequency signals over these networks the listener could be given a choice between the audio method and the high-frequency method. While the high-frequency method is more advantageous from the point of view of the number of programmes which can be disseminated, the audio system is preferred by the subscriber who wants the minimum of apparatus in his home.

Dr. L. E. C. Hughes: There is no real competition between broadcasting over power mains and over telephone circuits, provided the same service is given by each. Both types ought to be developed along reasonable commercial lines, because technically both offer substantially the same grade of reproduction and number of channels. One cannot regard the push-button receiver demonstrated by the author as representing a satisfactory standard of reproduction, because a standard of reproduction clearly implies a definition which complies with the well-known criteria for faithful reproduction, in this case applying to a single channel. Moreover, the quality obtainable with such mass-produced receiving sets is very variable, and does not improve as time goes on. A standard of radiated reproduction has not yet been defined by an authoritative body, but I would suggest to the author that the reproduction obtained with the non-modulated system over telephone lines might reasonably be taken as a good sample of what can be attained in reproduction nowadays. The public would then be able to judge the value of reproduction from other types of receiving apparatus if they had this reference easily available. In making the reproducers on a large scale, the average quality of reproduction must inevitably be somewhat less than is obtainable in a laboratory-constructed equipment; how is the tolerance of departure from the reference to be determined, and by whom assessed?

Mr. A. J. Gill: I think the title "Wire Broadcasting" is rather inappropriate, because with this system the programme is not distributed anywhere and everywhere but is sent exactly where it is wanted.

I notice that the author made some tests using oil-impregnated paper cables, and it would be interesting to know whether he considered making tests with the ordinary dry paper cable used for telephonic purposes. Where oil-impregnated paper cables are used it is usually necessary to seal the ends so that leakage of oil is pre-

vented; perhaps he would explain how sealing is obviated in this case.

The fact that only 3 % of the listeners in this country receive their programmes by wire may be due partly to the uncertainty of the position which has prevailed up to now, and partly to the fact that in some cases the local authorities have opposed the introduction of wire broadcasting. There is some objection to an additional authority opening the streets in order to lay cables, and there is a good deal to be said either for incorporating the wire broadcasting in the Post Office telephone system or for the supply authorities using their cables for the purpose.

Dr. Smith-Rose mentioned the possibility of direct radio interference on receivers, and the consequent need for screening. I take it that the band used here is the long-wave band, however, and that the noise level is relatively high so that a small amount of radiation from the line system would be unnoticed. As for the absence of noise, which Dr. Smith-Rose finds surprising, the noise limit which we try to set on telephone trunk lines is about 55 db. below ordinary speech value, so that when there is anything else on the line the noise should not be noticed. The noise is mostly of audio frequency, and therefore there would be little or no trouble at the carrier frequencies. In electrical laboratories and works induced noise may be present, but this is not usually the case in residential areas where a wire broadcasting system would be used.

Mr. H. B. Rantzen: An important factor in programme reception by any means is the motive which prompts the listener to receive a particular programme—whether, for example, it is a desire to exercise his skill in handling his receiver or merely his wish to be entertained. Most of the wire systems which have been constructed so far have been presented as a complete alternative to radio reception, very largely in areas where a satisfactory wireless signal is not available. As far as the Post Office carrier system is concerned, I think that not many people can be expected to install a system in which four programmes coming in by line can be received only by having a complete wireless set. It seems a pity that the good signal-strength obtainable by line should have to go through the high-frequency side of commercial sets, many of which are designed almost like communication receivers in this respect.

I think the economics of the system, and possibly the method of distribution, might have been very different if the number of programmes had been reduced to two. In these circumstances, low-frequency distribution of the programme might prove economical. This might also have led to the development of sets in two parts: a very selective high-frequency stage, followed by a high-quality low-frequency receiver. The complete set must be available either for distant listening or for high-quality home reception. Generally speaking, so far, there have not been more than two programmes available for home listening.

Fig. 19 shows a distribution system which is partly audio-frequency and partly carrier-frequency. I should be glad if the author would tell us at what levels he feeds the two types of signals to line, and what sending impedances he uses. It seems to me that in some cases there will be difficulties in providing the necessary power to be fed into very low impedances. What is the proper input-voltage level to his 15 000-ohm loud-speaker?

Seeing that the paper deals with so many complicated line transmission problems it contains surprisingly few references to cross-talk. It has been my experience that when dealing with lines alone, from terminal to terminal, one can often expect a signal/noise ratio of about 90 db. But as soon as exchange apparatus is installed at the terminal, the figure comes down to about 50 db.

Referring to Fig. 4, I notice that the protective equipment has been left in the lines in the programme circuit, and I should like to know whether this gives rise to any difficulties. In dealing with outside broadcasts we try to reduce the protective equipment to a minimum.

If in a cable there are 20–30 pairs all carrying carrier frequencies with their programme modulations on them, the cross-talk may be sufficient to ensure that the carrier is on every pair in that cable. In high-frequency work on local telephone cables we found that low levels of very high-frequency energy travelled down the cable, apparently between the centre of the cable and the lead sheath.

I should be glad if the author would confirm that he has always found it necessary to connect up to every pair in the cable that has to be fed with programme.

Mr. G. C. Marris: The quality of the reproduction is one of the factors which will decide the success of a wire broadcasting system. Another factor is the quality of the standard broadcast receivers and loud-speakers which are available.

Despite the remarks of Dr. Hughes the fact is that, judged by performance curves, by power output, by freedom from harmonics and by reports from skilled listeners, the quality of reproduction given by radio receivers has been improved rapidly in the last few years.

I should like to ask the author what power per loud-speaker he thinks is a usual figure on audio systems.

Mr. E. M. Lee: I should like to make a few remarks on the subject of the suppression of interference. I have been trying for a number of years to persuade the public to pay just a little to have their interference cured; but I find that they always want it cured for nothing, and I am very pessimistic about their paying even 1s. a week to get interference-free reception. I am afraid that so many of the best Post Office technicians may concentrate their attention on the wire broadcasting system that they will be unable to push through the legislation at which we have been aiming for years to compel the suppression of interference from electrical appliances.

Mr. W. A. C. Maskell: When considering the justification for a wire broadcasting system in comparison with other systems of reception such as radio receivers there are three points which have to be borne in mind. The first is the strategic angle (in time of war), the second the economic angle and the third the necessity of providing what the public want with regard to reproduction.

The economic question is bound up with the price at which the Post Office can offer its service to the public. The listener has to consider whether the alleged better quality and limited number of stations given by wire

broadcasting for, say, 1s. 3d. a week is more valuable than all one can get on a radio set to-day with long, medium and short waves.

As regards the third point, which is really the question of quality, in the author's demonstration we have heard the engineer's conception of quality. From a considerable amount of experience I am prepared to say that that is not what the public as a whole require, and the question is whether we set out to educate the public to the engineer's standard or let them judge for themselves. We can reproduce speech at roughly the same value as that at which it was delivered and get an excellent equivalent to the original, but music is a different problem and must of necessity be a compromise. I think, therefore, that the failure to provide any form of variable tone balance on the Post Office equipment is a great mistake.

[The author's reply to this discussion will be found on page 105.]

DISCUSSION BEFORE THE MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 15TH JANUARY, 1940

Prof. E. W. Marchant: One of the first wire broadcasts of music occurred in about 1897, when the late Mr. Duddell, who was experimenting at the City and Guilds College with the oscillating arc, made up a keyboard with which it was possible to play a tune. The electric oscillations from the arc were transmitted along the street mains, with the result that passers-by in Exhibition Road heard, to their amazement, the tune of "God Save the King" coming from the street arc lamps; and I believe the same effect was observed in one of the lecture rooms of the Royal College of Science, where an arc lamp was being used for a lantern.

It is surprising to learn that, in Holland, over 50 % of the listeners use wire distribution. The difficulty in connection with a wire broadcast is that the cable system requires maintenance and a relatively heavy capital expenditure. Technically there is no serious difficulty in regard to the transmission, provided there is uniform attenuation in the cables at all frequencies. The problem is the same as that of a telephone transmission, and for good results special cables must be employed. It is quite evident that an ordinary cable such as is used for power transmission has not the same characteristics as those required for a telephone transmission. On general grounds, therefore, there seems no doubt that the attempt to use a power-cable network for broadcast programmes is a retrograde step. It is worth while also to compare the cost of a two-programme service by wire broadcasting relay companies with the cost of radio transmission. The broadcasting relay service costs 1s. 6d. a week or £3 18s. a year, as compared with the 10s. paid for a wireless broadcast license; but for this latter payment and the maintenance costs set out in the paper an almost unlimited range of programmes is available. As regards the relative effectiveness of wire broadcasting at audio frequencies and at carrier frequencies, I think there is no doubt that the carrier is the more efficient, in just the same way as modern carrier systems of telephony have proved themselves much more efficient than audio-frequency circuits. The layout of the wire broadcasting stations is very similar to that of an ordinary telephone system, and the paper describes the complications involved in this sytem of transmission as compared with a radio system. It is rather significant also to see that, apart from the present paper, all the literature dealing with this subject is of German origin. I think, therefore, that, although the paper has technical interest, it is not likely to prove of any great practical utility in this country. A further disadvantage of wire broadcasting is that in the event of damage being done to the cable network a much larger number of subscribers are likely to be put out of action than would be the case if they were all using wireless sets.

A point also which is of some importance is that the strength of the signal received by different subscribers to a wire broadcasting system will be very different at different distances from the distribution centre, and that if they are to give the best results the receivers require individual adjustment, just like broadcast receivers.

May I suggest that it would be an advantage to avoid using the neper, which is now a defunct unit, and give all attenuations in decibels.

Mr. F. Mercer: The use of impregnated cable has certain advantages from a maintenance point of view but results in cables with higher attenuation.

Would it not be more satisfactory for the main feeder and for the distribution cables to be of the dry-core air-space paper-insulated type? The service cables, i.e. those leading directly into the listener's premises, could usefully be of the impregnated type, but would have little effect on the overall loss. Such an arrangement would be more efficient. There would also be a smaller difference in level between the upper and lower frequency limits, with consequent improved quality.

Mr. E. Blackburn: Some 6 or 7 years ago I was engaged on measuring the propagation characteristics of overhead trunk lines between 40 and 200 kc./s. One important point which emerged was the high value of the reflection losses which occurred at each change of gauge. The lines tested had a number of power crossings where the telephone lines were taken underground for a section of 100 yd. or so, and the losses at these points were so large that we had to design special matching transformers to obviate them.

The average telephone subscriber in a provincial suburban area has an underground-cable pair which has several changes of gauge of wire, and his line ends in one or more spares of open wire; I should therefore imagine that the reflection losses at the various changes of impedance characteristic will at least equal the line attenuation.

It appears to be the intention in the case of the carrier system to allow the use of the subscriber's radio set as part of the circuit. There are certain difficulties which have no doubt been taken into account. If an obscure or intermittent fault develops there will be need for the Post Office man and the radio service man to co-operate, and delay may result; also, if the receiving set is of

poor quality, the subscriber may get a bad impression of the Post Office service.

I am rather surprised that the loud-speaker chosen for the work should have an output characteristic rising by as much as 2·5 db. per octave. From my own observations, most sets having a tone control are worked with a bias in favour of the low notes, and I think it would be wiser to provide a speaker of level response with a tone control to enable the subscriber to satisfy his own tastes and conditions.

THE AUTHOR'S REPLY TO THE DISCUSSIONS

Dr. T. Walmsley (*in reply*): I agree with Mr. Eckersley that had conditions been different the number of listeners who received their programmes by wire in this country would have been more than 3 %. However, I am not sufficiently optimistic to believe that the figure would have reached 50 %.

The difficulties of introducing a buried network are realized, but it should not be forgotten that there is already in existence in this country a very extensive system of ducts that could be used for the purpose.

With regard to Mr. Eckersley's claim that electric supply mains go into 5 times as many houses as the telephone, it is pointed out in the paper that lines can easily be extended from telephone subscribers' circuits to non-telephone subscribers' premises. The additional expenditure required is not great but I am not at liberty to give any figures in this connection.

It is interesting to note that Mr. Eckersley found that, using special methods of distribution at lower frequencies, the necessary power per consumer was only 2 mW. This is very much larger than that required by receivers connected to a telephone system. Moreover, it is certain that in some areas where interference from power plant is severe 2 mW would be inadequate. The selector mentioned by him must necessarily be a radio receiver designed for a particular application.

Mr. Eckersley's statement, that it is more economical to energize each secondary network from separate repeaters, leads inevitably to the conclusion that with the type of distribution system in general operation in Great Britain a very large number of repeaters would be required. This contrasts very unfavourably with the requirements in a system utilizing a telephone network, where one local amplifier can provide for the needs of an area having a radius of approximately 2 miles. In the same area using the electric supply mains some dozens of amplifiers would be necessary. Furthermore, a secondary wire network would have to be provided to feed the programmes to the repeaters.

Mr. Eckersley stresses the difficulties due to low surge impedance of the electric supply network. It would be interesting to know how the difficulties have been overcome by careful design rather than by special devices.

Mr. West's remark, regarding the manner in which the levels available on the subscriber's volume control are fixed, presumably refers to the audio-frequency system. It will be appreciated that in this system distant subscribers will have a level several decibels lower than near subscribers. It is correct to assume that the normal setting of the volume control gives the loudness of the announcer's voice approximately the same as would be heard by a person in the room when joining in general conversation. In deciding the various levels, the opinions of a number of people were ascertained. The lowest level was such as to give a background of music such as not to prevent conversation, whilst the higher level satisfied a listener desiring somewhat strident sounds.

Dr. Smith-Rose asks how the difficulty of interference has been overcome in the use of apparatus connected either to power mains or to telephone lines. Two methods can be used for this purpose. The first is to render the carrier level so high as to overcome all interference effects. The second is to introduce high-frequency filters so as to reduce the noise within the band required by the receiver. In practice a compromise between these two methods is arranged, as far as the carrier over telephone wires is concerned. As already explained in the paper, the introduction of small filters presents no difficulties. In the case of distribution over power mains, however, the problem is much more difficult and generally a high carrier level is required. To ensure that direct reception of radio broadcasting stations is obviated, carrier frequencies are so chosen as to avoid interference from those broadcasting stations giving a high field strength in the locality concerned. Moreover, where an entirely underground telephone system is employed the field strength of interfering stations at the receiver is usually very weak.

In reply to Mr. Coombs, I have not carried out any research into broadcasting on high-frequency signals over open-wire networks of audio systems now in existence. Such a method of distribution is technically possible, although it is very doubtful whether it will yield any economic advantage.

I do not agree with Dr. Hughes that both types of broadcasting, viz. over power mains and over telephone circuits, offer substantially the same grade of reproduction, if he implies this is under similar technical conditions. My conviction is that, owing to the greater variation in noise and its higher average level, the electric supply system does not offer the same advantages as the telephone system.

Mr. Gill raises the question of the title "Wire Broadcasting" and points out that the term is inappropriate because with this system the programme is not distributed anywhere and everywhere. In our misguided optimistic days this is exactly what we hoped to do—hence the justification for the term!

The necessity for sealing oil-impregnated cables depends essentially upon the extent of the impregnation. The type of cable chosen was such that there was no leakage of oil from the ends, thus obviating the necessity for sealing. However, arrangements were made in each subscriber's premises to cover with a suitable compound the ends of the leading-in pairs where they entered the subscriber's connecting box.

I am inclined to agree with Mr. Rantzen that the weakness of any carrier system is that a complete wireless set is required at the receiving end. It should, however, be pointed out that a simplified form of set giving

better reproduction than that normally obtainable from a radio receiver is possible with a carrier system.

The levels at which signals are fed into the lines in a carrier system having transmitters connected to Post Office lines are as follows: Audio frequencies, single-level programme, 10 db. above 1 mW into 600 ohms, the programme level being adjusted so that peaks do not exceed this value. The carrier frequencies in junction circuits are fed at a level of 1 watt per unmodulated carrier into 150 ohms, and into the subscriber-circuit busbars at a level of 0·3 volt. The subscribers receive approximately 10 mV, adjustment being made at the exchange end of the line by means of coupling condensers so that this level is attained.

With regard to the 15 000-ohm loud-speakers used on the audio system, the voltage at the listener's end of the feeder was of the order of 85 volts. The experience of Mr. Rantzen when dealing with lines is somewhat unfortunate. It is agreed, however, that even though the cables themselves are quite good, end conditions can degrade the balance considerably.

I agree that the existence of protective equipment is a potential source of trouble. The cross-talk between pairs in the same cable is a variable quantity, but is very dependent on terminal conditions. Tests were made in the early days to ascertain whether it would be possible to feed by means of cross-talk a number of subscribers having pairs in a common cable, but this proved a complete failure. I agree, however, that in some cases, dependent upon the type and state of the cable, cross-talk might be appreciable.

Mr. Marris asks what power per loud-speaker is the usual figure on audio systems. If he means what power I feel should be allowed on normal strength, the answer is about 0·5 watt.

I can remove Mr. Lee's fears about Post Office technicians not being interested in the suppression of interference from electrical appliances.

Mr. Maskell is incorrect in thinking that the demonstration which I gave was an engineer's conception of quality. The views of a very large number of non-technical listeners were obtained and there was general agreement that the quality was excellent. A frequent comment by the listeners was that the quality of speech was such as enabled them to hear without effort. It is true that in a few cases listeners preferred a restriction in band width.

Most of Prof. Marchant's objections to wire broadcasting are dealt with in the text of the paper. There is little doubt at all that if the success of radio broadcasting and wire broadcasting depended upon quality, the wire broadcasting system would inevitably supersede the radio system. Prof. Marchant ignores this question of quality and rather evades the fact that in many cases a radio service costs as much as a wire-broadcasting service. Also, in the event of damage to the cable network a much smaller number of subscribers are likely to be affected than if a radio transmitting station broke down.

I agree with Mr. Mercer that oil-impregnated cables have a somewhat higher attenuation than dry-core air-space paper-insulated cables of the same dimensions, but in an audio system of distribution the difference is not such as to be serious. The attraction of the impregnated cable is its greater reliability. The puncturing of the lead sheath would not normally put the service out of action.

Mr. Blackburn refers to the additional loss due to mismatches occasioned by changes in the gauge of wire. Actually in practice the wires between exchanges and subscribers' premises have not the large number of changes in gauge which he appears to visualize, and no great difficulty has been experienced from this cause. He also mentions a real difficulty in the need for co-operation between the Post Office man and the radio service man.

The question of the loud-speaker characteristic is a controversial one. It is, however, significant that in the vast majority of cases where opinions have been taken the listener's preference has been for the type of loud-speaker described in the paper.

DISCUSSION ON "THE PLANNING OF STREET LIGHTING"*

Mr. R. Vine-Hall (Australia) (*communicated*): In the paper the author shows that mercury-vapour lamps operate to greater advantage in lanterns designed for horizontal mounting. While one must accept his argument as sound from the theoretical standpoint, there are some practical considerations which favour vertical mounting.

Apart from the most economical distribution of light, it is desirable that the lantern should be suitable for the rough conditions met with in street-lighting experience, both with regard to the weather and to suitability for cleaning and handling by the type of man who accepts engagement for maintenance of street lighting.

A number of lanterns similar in construction to that shown in Fig. 1 have been installed in Sydney, New South Wales, for comparison with other types, and after lengthy trials a lantern having a vertically burning lamp and a one-piece refractor has been adopted.

Theoretically, the distribution of light is superior in the lantern using horizontal mounting, especially when the unit is new. The lantern similar to Fig. 1 is, however, inferior in service for the following reasons:—

(1) Its composite nature renders its reflective and refractive surfaces liable to rapid deterioration due to dust and weather.

(2) It is difficult to clean.

(3) The metal edges throw disconcerting shadows across the road.

(4) The life of the horizontal-burning lamp is shorter, or the lamp itself less efficient, than the vertical-burning lamp.

(5) The lantern is more expensive.

(6) It is only applicable to lamps of tubular shape, viz. 400 watt and 250 watt.

The standard lantern for vertical-burning lamps has, on the other hand, none of these disadvantages and gives good directional qualities to the light with the spacings and mounting heights recommended by the Ministry of Transport. The resulting street illumination is actually better after the first 6 months under service conditions than that from lanterns with horizontal-burning lamps.

Mr. J. Bertram (*in reply*): It is of interest to note that Mr. Vine-Hall agrees that the horizontal operation of discharge lamps is the most efficient method for obtaining the best light distribution and light control. I cannot agree, however, that the type of design shown in Fig. 1 is impracticable. It is possible that the earliest designs of horizontal lanterns, and even some on the market to-day, have been a source of trouble to the maintenance man, but the design described in the paper was the result of several years of field experience and is itself the essence of simplicity. One simple catch allows the lower refractor assembly to swing away from the lamp, leaving the whole of the interior of the lantern exposed for cleaning, without a single obstruction in the way.

With regard to Mr. Vine-Hall's other comments, I do not agree that the metal edges in the design illustrated in Fig. 1 throw disconcerting shadows across the road. The lower refractor was expressly designed to prevent this, and Fig. 2, which shows the shape of the distribution obtained from the unit, supports this view.

The fourth of the disadvantages enumerated by Mr. Vine-Hall is, in our experience, not applicable to the lamps and lantern discussed in the paper. A great deal can be said on this subject, and it has been discussed very fully in the *Electrical Review*.†

With regard to his sixth point, the lantern in question was expressly designed to give an accurate performance with the lamps in question and was not a general purpose unit for any type of lamp.

The simple round lantern is such an attractive manufacturing proposition that only substantial advantages, such as reduction of glare and greater efficiency of light distribution, could lead manufacturers to depart from it.

* Paper by Mr. J. Bertram (see *Journal I.E.E.*, **85**, p. 649).

† *Electrical Review*, 1936, **118**, p. 309; and 1938, **122**, p. 681.

INSTITUTION NOTES

CENTRAL REGISTER OF NATIONAL SERVICE

The attention of those members who have not returned their Central Register cards is drawn to the appeal issued last month by the Minister of Labour and National Service, a copy of which appeared on page 609 of the June issue (No. 522) of the *Journal*. The Minister will expect a full response from the membership of the professional Institutions to this appeal, which must be the last stage in the process of voluntary registration. The Council therefore hope that the desire of the members of The Institution to assist the Minister in the steps he is taking will be demonstrated by a very full response.

Changes now taking place in the organization of the Central Register, and the issue of certain new regulations, render it essential that all engineers shall be enrolled; and it is understood that on the completion of the present registration further steps will be taken for this purpose.

DISTRIBUTION OF THE JOURNAL IN 1941

The returns of the questionnaire issued to every member on the 30th May are far from complete, and the Council would therefore be glad if those members who have omitted to fill in and return the reply form would do so as soon as possible.

The re-organization of the distribution of the *Journal* is throwing a heavy burden on a depleted staff, who at the same time are otherwise actively engaged on many matters directly connected with the war effort. In the absence of any indication of a member's wishes, it will therefore have to be assumed that he does not desire to receive any copies of the *Journal* other than Part I after the 31st December, 1940; and unless at least three months' notice in advance is given it will probably be impossible to commence the regular despatch of Parts II and III to those members who have not returned their reply forms.

A copy of the circular letter which accompanied the questionnaire and in which the re-arrangement and subdivision of the *Journal* are described will be found on page 611 of the June issue (No. 522) of the *Journal*, and any member who has mislaid the questionnaire can obtain a further copy on application to the Secretary.

THE RECEPTION OF MEMBERS' CHILDREN IN CANADA

The Institutions of Civil, Mechanical and Electrical Engineers are in touch with the Engineering Institute of Canada in regard to a proposal from that body whereby members of the three Institutions who are sending their children to Canada for the period of the war through the Children's Overseas Reception Scheme, and who have no relatives or friends in that country to whom to send them, might be able to arrange for their children to be received into the homes of Canadian engineers.

As the proposal is still under consideration no particulars can be given at present, but it is hoped to make a further announcement on the subject shortly.

A member of The Institution of Electrical Engineers wishing to obtain further particulars of the scheme when available should communicate with the Secretary.

PREMIUMS

In addition to the Premiums mentioned on pages 610 and 611 of the June issue of the *Journal* (vol. 86), the Council have awarded the following Premiums for papers read before the Students' Sections during the Session 1939–40:—

Premiums of the value of £10 each:

Author	*Title of Paper*	*Where read*
A. P. Harvey and H. A. Erith, B.Sc.	"The Proving of Oil Circuit-breakers under Short-circuit Conditions"	Newcastle
J. E. Houldin, Ph.D., B.Eng.	"Wave Guides, or Propagation of Electromagnetic Waves by Hollow Metal Tubes"	London
D. H. Ray	"Distribution System Control"	Birmingham

Premiums of the value of £5 each:

Author	*Title of Paper*	*Where read*
W. W. Campbell, B.Sc.(Eng.)	"Electrical Measurement of Mechanical Quantities"	Newcastle
A. T. Crawford, B.Sc.	"Engineering Training"	Newcastle
F. R. Haigh, B.Sc.	"Conductors for Overhead Power Lines"	Leeds
E. Jacks	"Testing-Station Design and Organization for the Smaller Supply Undertakings under the Electricity Supply (Meters) Act of 1936"	Manchester
A. E. Jepson, jun.	"Some Factors Affecting Thermostat Design"	Manchester
T. E. A. Verity, B.Sc.Tech.	"Methods of Recording Engineering Data"	Liverpool

OVERSEAS MEMBERS AND THE INSTITUTION

During the period 1st December, 1939, to 30th June, 1940, the following members from overseas called at The Institution and signed the "Attendance Register of Overseas Members":—

Arnot, R. S., B.Sc. (*Johannesburg*).
Bray, P. A. (*Kuala Lumpur*).
Broad, R. A. (*Brussels*).
Cameron, A. R., B.Sc. (*Singapore*).
Cater, C. (*Gold Coast*).
Cook, H. F., B.Sc.(Eng.) (*Kenya*).
Crisp, M. H. T. (*Burma*).
Dannatt, F. C., O.B.E. (*Paris*).
Dwyer, K. M. (*Johannesburg*).
Edwards, G. R. T., B.Sc. (*Rangoon*).
Field, H. J. (*Brisbane*).
Gibson, F. H. (*Penang*).
James, A. S., M.C. (*Madras*).

Marshall, H. W. S. (*Transvaal*).
Munro, G. H., M.Sc. (*Sydney*).
Prockter, C. E. (*Gold Coast*).
Sillar, K. G. (*Calcutta*).
Warren, Col. A. G. (*Lucknow*).
Young, J. A. (*Rangoon*).

BRITISH STANDARDS

The Secretary has been asked by the British Standards Institution to draw attention to the following new and revised Specifications:—

Method of Testing Dust Extraction Plant and the Emission of Solids from Chimneys of Electric Power Stations (B.S. 893).

As the industrial areas have developed, the number of coal-burning installations has increased and this has resulted in the problem of "smoke nuisance" becoming of considerable importance.

Some years ago the Electricity Commission set up a Committee to inquire fully into the problem in so far as it affected electric power stations, and in the report that was subsequently issued by this Committee the view was expressed that before the problem could be adequately tackled it was essential that there should be agreed Standards for:—

(*a*) A method of testing the emission of solids from chimneys.
(*b*) A method for determining and expressing the size of dust particles.

The task of preparing appropriate Standards was accordingly referred to the British Standards Institution and B.S. 893 has now been issued.

Mr. A. N. East of the Electricity Commission was the Chairman of the Committee responsible for preparing this publication.

Information on the subject which was available in this and other countries was obtained and examined. Where information was not available an attempt was made to obtain it by arranging for the necessary experimental work to be carried out. Accordingly the fact that a complete answer to the problem has not been obtained is due solely to the complexities of the problem rather than to a lack of their recognition.

It is hoped that the accumulated experience resulting from the adoption of the standard methods will provide material that will enable further progress to be made.

The Standard is in three essential parts as follows:—

Part 1. Method for the determination of the emission of solids from a chimney.
Part 2. Method for grading the dust by air elutriation.
Part 3. Descriptions of various forms of sampling tube which may be used in dust sampling.

A number of diagrams are included in the Standard and there is an appendix which deals with the problem of ensuring uniform and unidirectional flow of flue gases —one of the essentials for the reliable sampling of a dust-laden flue-gas stream.

The Standard will be of particular interest to all concerned with fuel combustion.

Copies of this Specification may be obtained from the British Standards Institution, 28, Victoria Street, London, S.W.1, price 5s. (5s. 4d. post free).

Test Code for Steam Turbines (B.S. 752).

The British Standard Specification for Steam Turbines (B.S. 132) and the British Standard Test Code for Steam Turbines (B.S. 752) are based on, and for all practical purposes identical with, the corresponding international documents issued by the International Electrotechnical Commission.

Since the publication of the Test Code in 1937, international agreement has been reached regarding a supplement to the Code, this taking the form of extensive notes on instruments and methods of measurement. These notes have now been incorporated as an Appendix to B.S. 752, thereby considerably increasing the usefulness of the Code. A further Appendix has also been included, this being reproduced from B.S. 108, Graphical Symbols, and shows the internationally-agreed symbols for use on diagrams of the layout of steam-turbine plant. The additional matter occupies 45 pages, thereby doubling the size of the document.

Copies of the revised British Standard may be obtained from the B.S.I., price 3s. 6d. each (3s. 10d. post free).

A.R.P. Signs (BS/ARP/32).

A British Standard Specification for A.R.P. Signs (BS/ARP/32) was issued in November, 1939, and laid down the size of the signs and the standard wording to be used. The degree of illumination was referred to only in general terms, and a note drew attention to the fact that it was hoped eventually to issue an addendum giving details of suitable lighting fittings.

The revision of the Specification which has just been published goes a good deal farther than this. There are 11 drawings illustrating various types of fittings for the lighting of location signs and direction signs, and reference is made to luminescent signs. The clauses dealing with the brightness and with the control of light have been amplified, and details of the method of testing signs for compliance with these clauses are included in an Appendix. This is a useful addition to the Specification, and manufacturers wishing to obtain licences for the use of the B.S.I. certification mark now know exactly what test conditions have to be complied with.

A further addition to the Specification is an Appendix on alternative lighting for emergency use, as a provision against the event of mains failure.

Copies of the revised British Standard Specification can be obtained from the B.S.I., price 6d. each (post free 8d.).

War-Time Street Lighting (BS/ARP/37).

With a view to allowing greater flexibility in the siting of street-lighting fittings, this Specification has been revised in respect of Clause 4 (Mounting Height and Spacing). No change has been made as regards the fittings to be used for spacings of not less than 100 ft., but additional information is now given as to how to install fittings in situations where the pole spacings are between 50 ft. and 100 ft.

This revision has been effected by means of a sheet, CF(ARP) 5597, and copies of this may be obtained from the B.S.I. on receipt of a stamped addressed envelope.

ROLL OF HONOUR (SECOND LIST)*

The following members have lost their lives in the service of their country:—

Killed in Action.

Collins, Sub-Lieut. (E.) F. H.	Royal Naval Volunteer Reserve	Graduate
Edgcumbe, Second Lieut. P. R.	12th Lancers	Graduate
Hampton, Sergt. D. A.	Royal Air Force	Graduate

Died.

Kerr, Signalman J. V.	Royal Signals	Student

The following member of the Institution staff has been killed in action:—

Blanchard, E. A.	Royal Artillery	Troop Sergt.-Major

MEMBERS ON SERVICE WITH H.M. FORCES (FIFTH LIST)†

(NOTE.—The Secretary will be glad to receive, for publication in subsequent lists, the names of other members of The Institution who are serving with His Majesty's Forces, together with particulars of their rank and the unit in which they are serving. A Roll of Honour, and lists of honours awarded, promotions, transfers, etc., are also being published from time to time.‡)

Members

Name	*Corps, etc.*	*Rank*
Bryden, J. E.	Air Formation Signals	Captain
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Meikle, J.	Royal Army Ordnance Corps	Major
Perks, J. N. R.	Royal Signals	Sec. Lieut.
Prangnell, N. W.	Royal Naval Volunteer Reserve	Lieutenant
Simpson, C. M.	Royal Engineers	Colonel

Associate Members

Name	*Corps, etc.*	*Rank*
Adams, G. C.	Royal Navy	Commander
Addison, E. B.	Royal Air Force	Wing-Comdr.
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Bennett, M. C.	Royal Signals	Major
Braendle, E. W.	Royal Air Force (V.R.)	Flt.-Lieut.
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Carr, W. B. H.	Royal Engineers	Captain
Cecil, The Hon. H. M. A.	Royal Navy	Commander
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Cooch, H.	Royal Air Force	Flt.-Lieut.
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Cropper, E. S. G.	Royal Air Force	Flt.-Lieut.
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Draeger, K. G.	Royal Naval Volunteer Reserve	Sub.-Lieut.
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Elsdale, R.	Royal Engineers	Colonel
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Fegen, R. F.	Royal Navy	Commander
Fuller, A. C.	Royal Signals	Colonel
Glass, C. G.	Royal Engineers	Major
Guthrie, A.	Royal Engineers	Major
Heath, F. J. R.	Royal Engineers	Captain
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Johnstone-Hall, F. C.	Royal Army Ordnance Corps	Major
Jones, P.	Royal Air Force	Wing-Comdr.
Jordan, R. J.	Royal Signals	Lieutenant
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Lewis, H. A.	Royal Army Ordnance Corps	Captain
Lewis, R. M. H.	Royal Engineers	Brigadier
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Meldrum, J. P. A.	Royal Signals	Captain
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Perowne, L. E. C. M.	Royal Engineers	Captain
Perryer, H. W.	Royal Engineers	Major
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Pulham, G. B.	Royal Naval Volunteer Reserve	Sub-Lieut.
Reeves, R. W. C.	Royal Signals	Captain
Richards, A. S.	Royal Engineers	Captain
Robinson, J. E. L.	Royal Artillery	Captain
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Ryan, R. J. H.	Royal Navy	Lieut.-Comdr.
Salter, J. R.	Royal Engineers	Captain
Schofield, A. J. A.	Royal Signals	Brevet Major
Shields, A. V.	Royal Signals	Captain
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Stillingfleet, R.	Royal Engineers	Captain
Taylor, J.	Royal Army Ordnance Corps	Captain
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Thursfield, D.	Royal Naval Volunteer Reserve	Lieutenant
Turner, C. W. C.	Royal Navy	Lieut.-Comdr.
Tuson, K. H.	Royal Engineers	Major
Tyack, F. G.	Royal Engineers	Lieutenant
Vaughan-Williams, H. L.	Royal Navy	Lieut.-Comdr.
Wade, D. A. L.	Royal Signals	Lieut.-Col.
Wainscot, F. S.	Royal Air Force (V.R.)	Flt.-Lieut.
Walford, F. S.	Royal Navy	Lieut.-Comdr
Walker, G. N.	Royal Engineers	Major
Wheatley, M. S.	Royal Signals	Major

* See *Journal I.E.E.*, **86**, p. 510.
† *Ibid.*, **85**, p. 653; and **86**, pp. 99, 308 and 511.
‡ *Ibid.*, **86**, p. 510; and **87**, pp. 110 and 112.

Name	*Corps, etc.*	*Rank*
White, H. L.	Royal Engineers	Lieutenant
Woolfson, M.	Royal Naval Volunteer Reserve	Sub-Lieut.
Worlledge, J. P. G.	Royal Signals	Colonel
Wray, T. H. R.	Royal Naval Volunteer Reserve	Captain
Young, J. R.	Royal Engineers	Captain
Young, T. G.	Royal Army Ordnance Corps	Captain

Associates

Name	*Corps, etc.*	*Rank*
Dean, R. P.	Royal Army Service Corps	Captain
Humphreys, H. V.	Royal Engineers	Lieutenant
Lord, I. G. S.	Royal Naval Volunteer Reserve	Sub-Lieut.
Manley, F. A.	Brigade Headquarters	Colonel

Graduates

Name	*Corps, etc.*	*Rank*
Aitken, R. M.	Royal Army Ordnance Corps	Lieutenant
Alesworth, F. R.	Royal Engineers	Sec. Lieut.
Allan, J. D.	Royal Army Ordnance Corps	Captain
Almond, G.	Royal Naval Volunteer Reserve	Lieutenant
Bartlett, F. W. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Bayley, R. M.	Royal Army Ordnance Corps	Staff Sergeant
Bradshaw, H.	Royal Naval Volunteer Reserve	Sub-Lieut.
Brooke, E. R.	Royal Navy	Telegraphist
Bury, R.	Royal Engineers	Lance-Corporal
Buxton, A. J.	Royal Air Force (V.R.)	Pilot Officer
Cowper, A. A. T.	Royal Army Ordnance Corps	Lieutenant
Cox, E. F.	Royal Naval Volunteer Reserve	Sub-Lieut.
Dykes, J. O.	Royal Air Force (V.R.)	Pilot Officer
Edward, A. W.	Royal Navy	Torpedo Officer
Eldred, E. M.	Royal Air Force (V.R.)	Flt.-Lieut.
Euler, H. L.	Royal Naval Volunteer Reserve	Lieutenant
Evans, J. D.	Royal Naval Volunteer Reserve	Sub-Lieut.
Fisher, A. J. M.	Royal Artillery	Sec. Lieut.
Franklin, W. A.	Royal Navy	Electrical Artificer
Garnett, W. H.	Royal Air Force (V.R.)	Pilot Officer
Goudge, K. A.	Royal Naval Volunteer Reserve	Sub-Lieut.
Gunton, R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Hancock, G. N.	Royal Air Force	Squadron Leader
Harris, A. W.	Royal Army Ordnance Corps	Lieutenant
Harris, L. F.	Royal Army Service Corps	Private
Heanen, J. A.	Royal Army Ordnance Corps	Lieutenant
Heins, J. P.	Royal Naval Volunteer Reserve	Sub-Lieut.
Hill, J. W.	Royal Army Ordnance Corps	Sec. Lieut.
Hill, R.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Hitch, F. A. N.	Royal Engineers	Lieutenant
Hutchison, W. M.	Royal Naval Volunteer Reserve	Sub-Lieut.
Hutty, W. D.	Royal Navy	Sub-Lieut. (E)
Ilsley, J. L.	Royal Army Ordnance Corps	Lieutenant
Inman, J. D.	Royal Engineers	Sapper
Jackson, G. S.	Auxiliary Military Pioneer Corps	Private
Jones, L. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Keeling, J. P. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Kennedy, J. D.	Royal Army Ordnance Corps	Lieutenant
Kirkland, E.	Royal Artillery	Sergeant
Kitchen, F. H.	Royal Army Ordnance Corps	Lieutenant
Knowlson, W. J.	Royal Artillery	Gunner
Macan, R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Marshall, H. W. S.	Royal Naval Volunteer Reserve	Sub-Lieut.
Marshall, R. V.	Royal Army Service Corps	Private
Martin, R. A.	Royal Signals	Signalman
Mears, R. J.	Royal Army Ordnance Corps	Lieutenant
Miller, J.	Cameron Highlanders	Corporal
Pannell, J. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Parsons, J. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Percy, J. D.	Royal Naval Volunteer Reserve	Sub-Lieut.
Pikett, C. C.	Royal Signals	Sec. Lieut.
Pipkin, F. E. R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Powditch, R. V.	Royal Army Ordnance Corps	Lieutenant
Pringle, T. A.	Royal Air Force (V.R.)	Pilot Officer
Ramsay, G. J. H.	Royal Army Ordnance Corps	Lieutenant
Richmond, J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Rye, A. R.	Royal Naval Volunteer Reserve	Lieutenant
Slater, I. G.	Royal Army Ordnance Corps	Lieutenant
Sneath, W. S. G.	Royal Engineers	Sapper
Steel, J. E.	Royal Army Ordnance Corps	Lieutenant
Stockton, D. A.	Royal Air Force	Sergeant
Stott, J.	Royal Army Service Corps	Captain
Thomas, N. E.	Royal Signals	Sec. Lieut.
Toule, J. H.	Royal Army Ordnance Corps	Lance-Corporal
West, P. E. F.	Royal Naval Volunteer Reserve	Lieutenant
Wilson, T. C.	Royal Signals	Lance-Corporal
Woodbridge, G. L.	Royal Air Force (V.R.)	Flt.-Lieut.

Students

Name	*Corps, etc.*	*Rank*
Adams, E. F.	Officer Cadet Training Unit	Cadet
Adcock, S. F.	Officer Cadet Training Unit	Cadet
Allison, J. W.	Royal Air Force	Sergeant
Bettinson, S. F.	Royal Air Force	Corporal
Blandford, F. A.	Officer Cadet Training Unit	Cadet
Bower, L. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Browne, G. J.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Carnegie-Rumboll, J.	Royal Army Service Corps	Driver
Carsbury, W. H.	Royal Signals	Signalman
Chad, D. W.	Royal Air Force (V.R.)	A.C.2
Chamberlain, D. A.	Royal Signals	Lance-Corporal
Cooper, D. H.	Royal Air Force	A.C.2

Name	Corps, etc.	Rank
Davies, E. J. L.	Royal Air Force	A.C.1
Decottignies, E. M. E.	Royal Medical Naval Reserve	Surgeon-Comdr.
Druce, K.	Royal Naval Volunteer Reserve	Sub-Lieut.
Fowler, D.	Royal Artillery	Battery Sergt.-Major
Gilchrist, J. A.	Royal Naval Volunteer Reserve	Sub-Lieut.
Grant, F.	Royal Air Force	A.C.2
Griffiths, F.	Divisional Provost Company	Lance-Corporal
Harris, J.	Royal Air Force	A.C.2
Hase, T. L M.	Royal Signals	Sec. Lieut.
Hutchings, C. G.	Royal Air Force (V.R.)	Aircraftman
Hyamson, T. D.	Royal Engineers	Sec. Lieut.
James, A. B.	Royal Naval Volunteer Reserve	Sub-Lieut.
Jones, A. B.	Royal Artillery	Gunner
Jones, C. W.	Royal Naval Volunteer Reserve	Lieutenant
Jones, D. S. A.	Royal Army Ordnance Corps	Private
Kitchener, R. D.	Royal Naval Volunteer Reserve	Sub-Lieut.
Lindsay, D. G.	Royal Artillery	Mechanist Sergt.-Major
Marshall, E.	Royal Signals	Signalman
Mohan, A. S.	Royal Air Force (V.R.)	Pilot Officer
Moore, T. E. R.	Fleet Air Arm (R.N.)	Naval Airman
Morris, A. R.	Royal Air Force	A.C.2
Morton, G. B. S.	Royal Air Force	Corporal
North, C. A.	East Surrey Regt.	Private
Pallant, E. W.	Royal Engineers	Sapper
Pike, W. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Porter, A. H. J.	Royal Air Force	A.C.1
Powell, G.	Royal Signals	Lance-Sergeant
Pratt-Johnson, W. H.	Royal Naval Volunteer Reserve	Sub-Lieut.
Quance, G. C.	Royal Air Force (V.R.)	Aircraftman
Sampson, D. P.	Royal Signals	Lance-Corporal
Stanley, J. G. H.	Royal Naval Volunteer Reserve	Sub-Lieut.
Strachan, D. A.	Royal Air Force (V.R.)	Pilot Officer
Thomas, G. B. S.	Royal Naval Volunteer Reserve	Sub-Lieut.
Watson, W.	Royal Engineers	Sapper
Woodbam, S. H.	Royal Signals	Signalman

Institution Staff

Name	Corps, etc.	Rank
Brown, K. W. T.	Royal Engineers	Sapper
Denford, H. F.	Royal Artillery	Gunner

PROMOTIONS AND TRANSFERS OF MEMBERS ON SERVICE WITH H.M. FORCES (THIRD LIST)*

Member

Name	Corps, etc.	Rank
Jones, J. E.	Royal Engineers	Captain

* *See Journal I.E.E.*, **86**, p. 510.

Associate Members

Name	Corps, etc.	Rank
Allerston, P.	Royal Air Force	Flt.-Lieut.
Caley, L. P.	Royal Naval Volunteer Reserve	Lieutenant
Chard, F. de la C.	Royal Signals	Captain
Clarke, H.	Royal Air Force	Flt.-Lieut.
Colvin-Smith, P. M.	Royal Engineers	Lieutenant
Fayle, L. R. E.	Royal Engineers	Major
Hounsfield, R. B.	Royal Naval Volunteer Reserve	Lieutenant
Mathews, D. C. H.	Royal Engineers	Captain
Straughen, A. R.	Royal Naval Volunteer Reserve	Lieutenant
Verity, A. S.	Royal Engineers	Lieutenant
Walton, W. F. J.	Royal Naval Volunteer Reserve	Lieutenant

Graduates

Name	Corps, etc.	Rank
Armstrong, G.	Royal Naval Volunteer Reserve	Lieutenant
Brooks, H. W.	Royal Naval Volunteer Reserve	Lieutenant
Callender, M. W.	Royal Naval Volunteer Reserve	Lieutenant
Campling, J. N.	Royal Naval Volunteer Reserve	Lieutenant
Gallop, P. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Gill, J. A. W.	Royal Naval Volunteer Reserve	Lieutenant
Hickling, C. G.	Royal Naval Volunteer Reserve	Lieutenant
Matthews-Hunter, C.	Royal Army Ordnance Corps	Captain
Parton, J. E.	Royal Naval Volunteer Reserve	Lieutenant
Payne, S. L.	Royal Naval Volunteer Reserve	Lieutenant
Rice, N. R.	Royal Naval Volunteer Reserve	Lieutenant
Robinson, H. R.	Royal Naval Volunteer Reserve	Lieutenant
Streatfield, E. C.	Royal Signals	Lance-Corporal
Tessier, R. L. C.	Royal Naval Volunteer Reserve	Lieutenant
Wright, J. D.	Royal Artillery	Lance-Sergeant

Students

Name	Corps, etc.	Rank
Collard, J. G.	Yorks and Lancs Regt.	Sec. Lieut.
Hale, N. V.	Royal Signals	Lance-Corporal
Jones, C. W.	Royal Naval Volunteer Reserve	Lieutenant
Tough, J.	Royal Naval Volunteer Reserve	Sub.-Lieut.
Trapnell, A. H.	Royal Army Ordnance Corps	Lance-Corporal

Institution Staff

Name	Corps, etc.	Rank
Arnold, G.	Royal Air Force	Corporal


BEHIND THE BLACK-OUT
Abnormal Consumption demands
FERRANTI
ACCURACY
in Metering Essential Supplies
In the factory, increased consumption of electricity due to the black-out, arising from the additional use of light during the day, as well as of light and power through the night, places an exceptional responsibility upon the registering equipment.
These abnormal conditions reveal a very real need for fine and sustained accuracy in metering such as is provided by the precision and stability of Ferranti Polyphase Meters FLx and FLy.
For 3-phase unbalanced systems, Ferranti 3-wire and 4-wire Meters are the most compact types available.
Note the dimensions.
3-phase, 3-wire, FLy (2 elements). 5.7" wide. 6.8" high. 4.6" in depth.
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This remarkable result is achieved by unique and ingenious design, which in conjunction with its fine accuracy characteristics, makes Meter easily the best polyphase metering.
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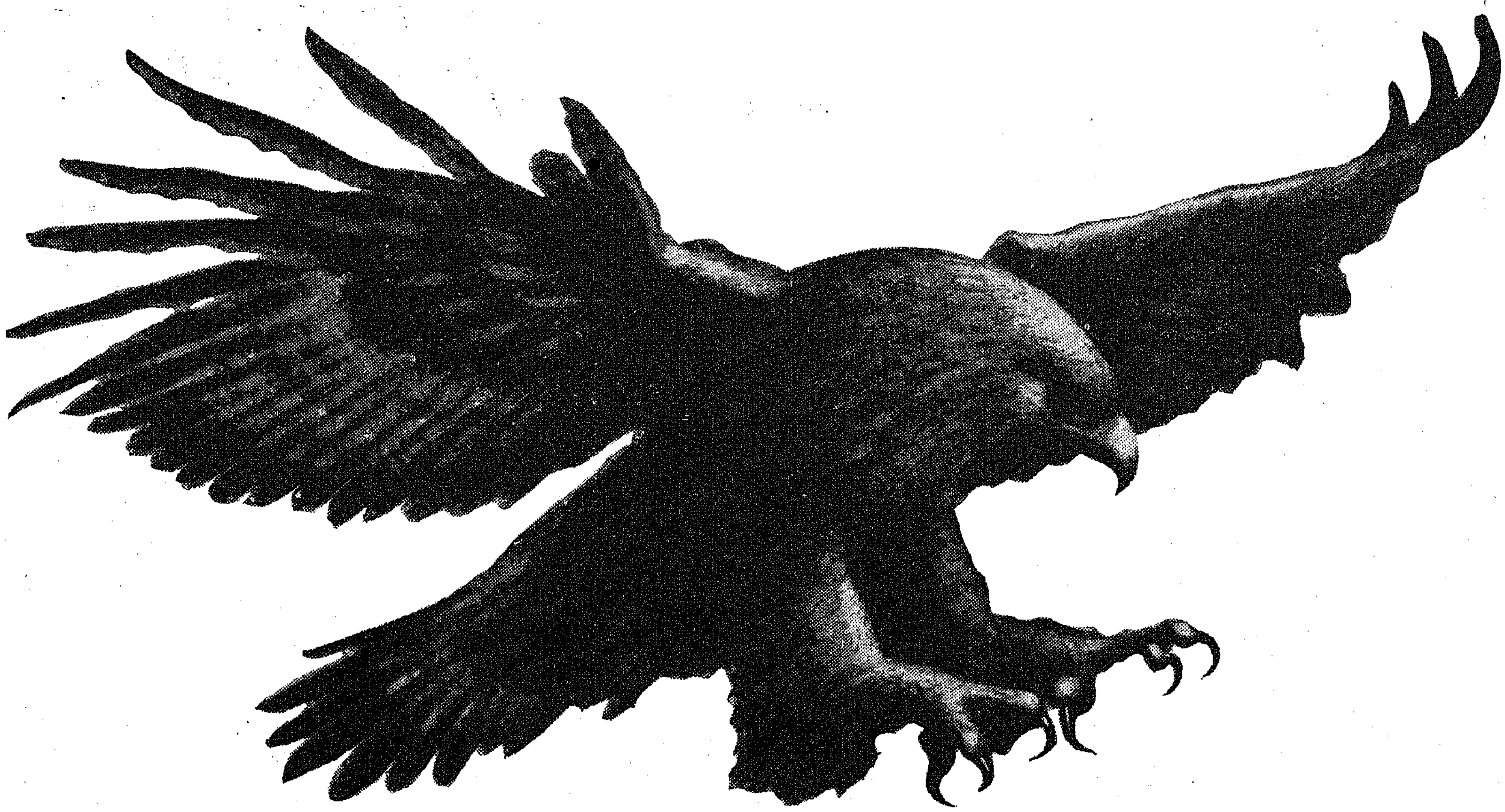

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West Wales (Swansea) Sub-Centre.

Chairman.—A. Rees.
Hon. Secretary.—R. Richards, 78, Glanbrydan Avenue, Swansea.

Hampshire Sub-Centre (directly under the Council).

Chairman.—W. S. Lonsdale.
Hon. Secretary.—A. G. Hiscock, c/o City of Portsmouth Electricity Undertaking, 111, High Street, Portsmouth, Hants.

Northern Ireland Sub-Centre (directly under the Council).

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Hon. Secretary.—C. M. Stoupe, B.Sc., 32, Kansas Avenue, Belfast.

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Chairman.—F. E. J. Ockenden.

TRANSMISSION SECTION.

Chairman.—F. W. Purse.

WIRELESS SECTION.

Chairman.—E. B. Moullin, M.A., Sc.D.

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Hon. Secretary.—C. A. Saxby, Electrical Engineering Branch, Dept. of Public Works, Bridge Street, Sydney.

Queensland.

Chairman and Hon. Secretary.—J. S. Just, c/o Box 1067n, G.P.O., Brisbane.

South Australia.

Chairman and Hon. Secretary.—F. W. H. Wheadon, Kelvin Building, North Terrace, Adelaide.

Victoria and Tasmania.

Chairman and Hon. Secretary.—H. R. Harper, 22-32, William Street, Melbourne.

Western Australia.

Chairman.—J. R. W. Gardam.
Hon. Secretary.—A. E. Lambert, B.E., c/o City of Perth Electricity and Gas Dept., 132, Murray Street, Perth.

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Chairman.—S. W. Redclift.
Hon. Secretary.—D. H. P. Henderson, c/o Calcutta Electric Supply Corporation, Post Box 304, Calcutta.

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Chairman.—V. F. Critchley.
Hon. Secretary.—Saudagar Singh, M.Sc., Electrical Engineer to Government, Punjab, McLeod Road, Lahore.

Madras.

Chairman.—E. J. B. Greenwood.
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